Contemporary and past conditions in the Hurunui River hapua, Canterbury, New Zealand, and the potential effects of dams on this lagoon.

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Abstract

Hapua are complex and dynamic systems, and are especially vulnerable due of their location at the end of river catchments. The Hurunui River hapua is currently under pressure from the intensification of irrigation and agriculture, and a number of dam proposals in its catchment. The purpose of this research was to investigate the current conditions in the Hurunui River hapua, how they respond to the observed range of contemporary catchment and coastal processes, and to examine of the longer-term behaviour and vulnerability of the hapua. This information was then used to make predictions on how the hapua could be impacted if dams were to be built in the catchment, or if significant changes in the catchment occur.

A multidisciplinary approach was used to investigate the short-term baseline conditions, and the long-term geomorphology of the Hurunui River hapua. Water characteristics were investigated over a falling tide, in different areas of the hapua, and in different energy conditions. The short-term behaviour of the hapua was investigated using hourly images from a time-lapse camera. The long-term vulnerability over decadal time scales was analysed using aerial photographs.

This study showed that the flow of the river, the shape of the hapua, and the position of the outlet has a major control over the characteristics of the water. The surface area, the position of the barrier, and the width of the barrier of the Hurunui River hapua have been variable historically.

From this research, it is predicted that the greatest impact on the Hurunui hapua would result if there is a dam related change the shape and outlet of the hapua to a state that reduces water residence time and decreases water quality. It is also predicted that if the outlet is maintained at the northern end of the hapua, and no ponded areas are present, that there would be the least problems with water quality.

The findings of this research have improved the understanding of the water characteristics and processes of the Hurunui River hapua, and how they respond to change.

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Chapter 1: Introduction

1.1 Thesis statement

Hapua are a type of mixed sand and gravel coastal lagoon that form an interface between fluvial and coastal environments (Kirk, 1991). The morphology of hapua depends on the balance between fluvial and coastal processes, as well as the characteristics of the barrier. Because of their location at the end of river mouths, they are sensitive to changes in their river catchments (Hart & Bryan, 2008). Like almost all hapua in Canterbury, the Hurunui River hapua is currently under a range of pressures from its catchment including irrigation and agriculture, and in the future, a number of proposed dams (Canterbury Water *et al.,* 2011; Environment Canterbury, 2011g), which may make the situation more complex. Current lagoon system pressures are expected to increase, and new pressures arise if dams are built and water availability is increased for irrigation and agriculture (Brown *et al.,* 2011). With its river at the forefront of national-level changes to water resource infrastructure and management, the Hurunui hapua is at a significant crossroad in terms of the changing relationship between freshwater environments and the coast in New Zealand. This thesis examines the current state and likely future state of the Hurunui hapua in the context of dam proposals.

To date, a number of reports have examined the range of potential fluvial impacts from the proposed dams on the Hurunui River and Waitohi Rivers post development. These have included: Boffa Miskell Limited, 2011; Chin, 2009, 2011; Chris Hansen Consultants Limited, 2011; Christensen & Torgersen, 2011; Hicks, 2011; Keesing, 2011a, 2011b; Lin, 2009; Mosley, 2002; Peter Rough Landscape Architects Limited, 2009; and Ward & Veendrick, 2009. Impacts identified include those on the river ecology, morphology, recreation, and amenity values of the Hurunui and Waitohi Rivers (Boffa Miskell Limited, 2009; Hicks, 2011; Lin, 2009; Ward & Veendrick, 2009).

However, it is currently unknown how the proposed dams could impact the river mouth lagoon environment. The health of the hapua is regarded in terms of water quality and its ecology. Although it has been identified that there are likely to be negative impacts on the health of the hapua if dams are to be built, the exact impacts are unknown and have been largely ignored (e.g. in: Whitehouse, 2011; Chin, 2009, 2011; Hicks, 2011). It is also assumed that the current minimum flows in the Hurunui-Waiau Regional Plan are sufficient for keeping the river mouth open and maintaining the current state of hapua health (Whitehouse *et al.,* 2011). However, the mouth of this river rarely closes due to its flow, so even if the mouth is open, the health of the hapua is not necessarily satisfactory.

While hapua geomorphology and the process balance that controls it has been well studied (Hart, 1999; Hart, 2007, 2009a, 2009b; Hart & Bryan, 2008; Kirk, 1983, 1991; Kirk & Hewson, 1979; Kirk & Lauder, 2000; McHaffie, 2010), there is virtually no information on biota in hapua and physio-chemical characteristics of the water column, and how these respond to change.

The focus of this study is to gather hapua baseline information to contribute to the existing literature. This baseline information includes sediment processes, and water quality characteristics in a range of common energy conditions that hapua experience. These energy conditions include floods, storms, and low energy conditions. The focus of this study is also to investigate spatial trends throughout the hapua. To assess the vulnerability of this system, the present behaviour and past geomorphology of the hapua will be studied.

This information is needed so that the impacts on the hapua from the dams can be determined if, in the future, the dams are built. It will also assist in any future evaluations of catchment activity changes such as agriculture intensification. **The purpose of this research is to contribute to, and complement, the existing literature on hapua by evaluating the current health of the Hurunui hapua, and how it responds to the observed range of contemporary catchment and coastal processes. The thesis then aims to use this present-day, pre-dam evaluation to postulate the potential aspects of the hapua system that may be sensitive to future dam development and catchment change. Lastly, it is expected that the results from this study could be used in the future (a) as a reference condition for the health of the Hurunui hapua, and (b) as a guide to develop a more comprehensive monitoring plan for hapua-type coastal systems.**

This study makes use of a range of monitoring and analysis techniques, some previously applied to hapua and others never applied in the form of a comprehensive hapua investigation. This is so that the current (day to day and intra-annual) health of the lagoon, and the vulnerability of this system to catchment change over long time periods (years to decades) can be evaluated. Monitoring in the field is used to gather baseline information, while aerial photographs are used to assess the longer-term vulnerability.

This chapter introduces the regional and international context with regard to coastal lagoons worldwide, hapua type coastal lagoons, and mixed sand and gravel coasts in section 1.2. This will also include the pressures that coastal lagoons and coastlines can experience from river catchments, especially dam developments. Following this will be the research context in section 1.3, giving details on the dam proposals in the Hurunui Catchment. This chapter will conclude with research gaps and objectives in section 1.4 and the structure of this thesis in section 1.5.

1.2 Regional and international context

1.2.1 Coastal lagoons

There has been much debate with regard to the classification and definition of both coastal lagoons and estuaries (Elliott & McLusky, 2002; Hume, 2003; Kirk & Lauder, 2000; Kjerfve & Magill, 1989; McLusky & Elliott, 2007; Tagliapietra *et al.,* 2009). Although often confused, coastal lagoons, especially hapua, have some distinguishing characteristics that separate them from estuaries (Tagliapietra *et al.,* 2009). Classification schemes have been developed according to various characteristics such as: ecology, geology, morphology, and tidal influence (Elliott & McLusky, 2002; Roy *et al.,* 2001). Kjerfve (1986) classified coastal lagoons as being choked, restricted or leaky. Choked lagoons have limited tidal influence, leaky lagoons have a number of permanent outlets and high tidal influence, and restricted lagoons are an intermediate state between the two (Kjerfve, 1986). Choked coastal lagoons on mixed sand and gravel coasts have been further classified as being either hapua (river dominated) or waituna (coastal lakes) in New Zealand (Hart, 1999; Kirk, 1991; Kirk & Lauder, 2000). While some definitions, such as those proposed by Kjerfve (1986), state that coastal lagoons experience an influx of seawater (Barnes, 2001), hapua do not (Hart, 2009a; Kirk, 1991). The classification of hapua is relatively well accepted (Hart, 2009a; Kirk & Lauder, 2000), in comparison to wider classifications of coastal lagoons and estuaries which to some extent is still debated (Elliott & McLusky, 2002; Tagliapietra *et al.,* 2009).

Coastal lagoons are particularly vulnerable to changes in their river catchments. This is because of their location at the end of river catchments, their limited exchange with the ocean, and their low volume-to-surface area ratio (Da Cunha & Wasserman, 2003; Lin & Hung, 2004). While there has been research on primary producers and biota in coastal lagoons (Da Cunha & Wasserman, 2003; Fong *et al.,* 1993; Meyercordt & Meyer-Reil, 1999; Pérez-Ruzaf *et al.,* 2008), these studies have not directly focused on the influence of catchment dams on these assemblages. Primary production in coastal lagoons has an important role in terms of filtering and modifying matter that is transported down the rivers (Kjerfve, 1994). Primary producers can include: cyanobacteria mats, phytoplankton, macrophytes, or benthic microalgae and macroalgae. It is thought that primary production in coastal lagoons may be controlled by a variety of factors such as lagoon area, lagoon volume, and tidal influence (Kjerfve, 1994).

The physico-chemical characteristics of the water in coastal lagoons are particularly sensitive to activities in the river catchment (Lucena *et al.,* 2002; Nixon, 1981; Pereira *et al.,* 2009; Sylaios & Theocharis, 2002). These activities can include a change in the flow regime due to dams, urbanisation, and agriculture (Sklar & Browder, 1998; Sylaios & Theocharis, 2002). Any change that does occur in the health of coastal lagoons will have implications for biota, and the effects can sometimes extend into the marine environment (Comin *et al.,* 1991; Hu *et al.,* 1998; Humborg *et al.,* 2000; Sklar & Browder, 1998; Snoussi *et al.,* 2007; Sylaios & Theocharis, 2002).

1.2.2 Hapua dynamics and processes

The river mouth of the Hurunui River has an associated coastal lagoon, otherwise known as a hapua. While these systems are underrepresented in the international literature (Beanish & Jones, 2002; Hart, 2007, 2009b; Hull *et al.,* 2008; Kirk & Lauder, 2000; Kjerfve, 1986; Kjerfve & Magill, 1989; Kjerfve *et al.,* 1996; Pereira *et al.,* 2009), they may not be as uncommon as is currently thought. Coastal lagoons are relatively common in New Zealand, especially along the Canterbury coastline (Hart, 2009a).

These coastal lagoons have a number of defining characteristics that make them unique. They are found in high energy wave environments, typically on chronically eroding or semi-stable coastlines (Hart, 2009a). The dynamic morphology of hapua depends on the balance between fluvial and coastal processes and the characteristics of the barrier, although for most of the time, hapua are dominated by wave processes (Figure 1.1) (Hart, 2009a). Hapua are found at the mouths of a range of river types, including large braided rivers originating in the Southern Alps, braided and meandering rivers originating in the foothills, and small meandering streams originating in the Canterbury Plains. Hapua barriers are composed of mixed sand and gravel. This sediment is transported down the rivers during floods and is then pushed onto the barrier via longshore drift (Hart & Bryan, 2008). Coastal lagoons in New Zealand have particularly high sediment loads, with annual yields significantly higher than the global average due to the steep bed gradients in their rivers (Kirk, 1991).

Another unique characteristic of Hapua is that they experience little, or no tidal influence (Kirk, 1991). The only time that hapua experience tidal action is immediately after a flood event when the hapua channel is enlarged and the flood waters recede, although this is not a frequent state. More commonly, saltwater may enter the lagoon via overtopping of waves over the barrier during flood events and by sea spray, although the river quickly flushes saltwater out of the lagoon (Hart, 2009a).

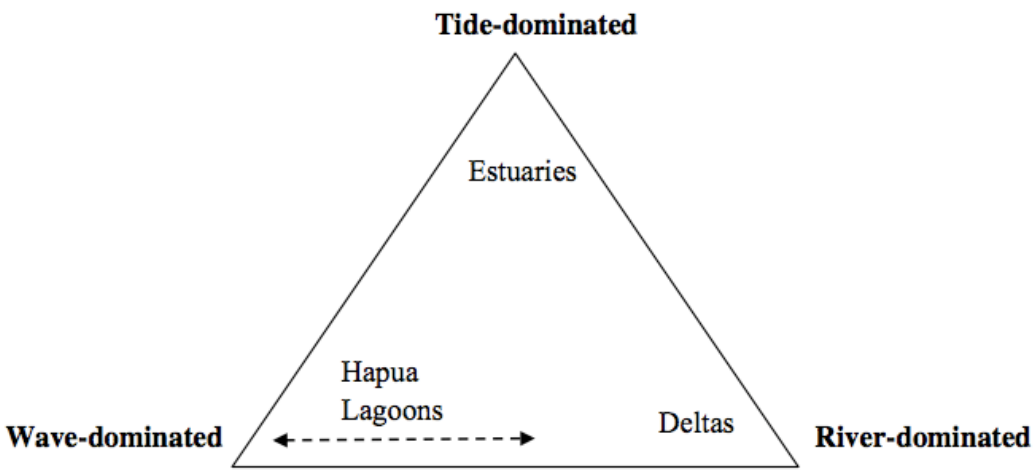


Figure 1.1: River mouth classification in Canterbury with regards to the degree of influence from tides, waves, and rivers. (Hart, 2007, p. 927).

Currently, there is concern about the sustainability and health of hapua. Because of their location at the end of river catchments, changes and activities in their river catchments are often more damaging than those occurring at the coast (Hart & Bryan, 2008). Of particular concern is the change in flow regime, especially the change in flood frequency, magnitude and duration since the morphology of hapua is especially sensitive to these controls (Hart, 2009a). Flood events are important for the movement of sediment downstream to the hapua, and for maintaining its size in the presence of landward retreat due to sea level rise (Hart, 2009a). A reduction in flood frequency and magnitude has the potential to reduce the amount of sediment reaching the hapua and the coast. Since the injection of sediment slugs is important for nourishing the hapua barrier and beaches along the coast, a change in the flood regime could increase erosion of the hapua barrier as well as the coast (Hart, 2009a).

The influence of river flow modification on hapua has been variable. The Ashburton and Opihi Rivers are susceptible to close during periods of low flows induced by irrigation draw off (Kirk, 1983). Flow regulation in the Rakaia River has resulted in an offset mouth to the north of the lagoon (Hicks, 2012). Alternatively, water regulation in the Waitaki River has resulted in the mouth being maintained adjacent to the river channel, and a shorter lagoon. The flow in the Waitaki and Rakaia Rivers is greater than the flow in the Ashburton River, and no closures of these river mouths have been recorded, both post and pre-dam (Hicks *et al.,* 2003).

Water quality in hapua is also sensitive to river flows. The greater the distance between the outlet and the main river channel, the longer the residence time the water will have, and the greater the chance for water quality to degrade within the lagoon (Hart, 2009a). Water abstraction also increases the risk of flooding since low flows can allow marine processes to dominate, leading to the barrier increasing in width and outlet/mouth offsets to increase in length (Kirk, 1991). Even small floods during periods of low flows can cause the outlet to migrate further northwards from the river channel, increasing the likelihood of the outlet closing, and leading to problems with water quality (Hart, 2007).

Hapua are also vulnerable to agriculture in their catchments. The influence of catchment agriculture on coastal lagoons has been evident in Waituna lagoon. Although this is a type of coastal lake, rather than a lagoon, the influence of catchment activities on the water quality is evident. Runoff from agricultural areas in the lagoon catchment has been identified as the likely cause for the degradation in water quality (Thompson & Ryder, 2003). The intensification of agriculture in New Zealand has also been a major contributor to the degradation in water quality in rivers (Ballantine *et al.,* 2010). Rivers with the poorest water quality are those that flow through urban and pastoral areas. Regardless of the varying trends between rivers, there is an overall decline in water quality in rivers in New Zealand (Ballantine *et al.,* 2010).

It is thought that hapua on eroding coasts persist over geological time since the landward shoreline retreats along with the landward retreat of the barrier (Hart, 2009b). However, this retreat landward is most likely dependent on the action of floods which ensure that the backshore of the hapua retreats along with the landward retreat of the barrier in response to sea level rise (Hart, 2009a). The backshore of the Hurunui hapua is composed of limestone cliffs, so the rate of retreat may be different to other hapua since limestone is eroded primarily by freshwater and sub aerial weathering. The potential reduction in floods and sediment transport to the coast, as well as the resistant backshore cliffs could potentially leave the Hurunui hapua at risk of dramatically reducing in size. This coastline, along with 75% of the coastline in the Canterbury region has been in an erosional state for a long time (Environment Canterbury, 2005). The current rate of erosion is estimated to be up to 3 meters per year along the majority of the Canterbury coastline, however it is thought that the Hurunui District has a lower rate of erosion, approximately 0.2 meters per year (Environment Canterbury, 2005). From 1950 to 2000, the size of the Ashburton hapua decreased by 50%. Although this hapua has different dynamics in terms of flow regime compared to the Hurunui, this should act as a warning that changes to flow regime can, and may have significant implications in terms of hapua area, especially at the Hurunui hapua (Hart, 2009a).

1.2.3 Mixed sand and gravel coasts

Mixed sand and gravel coasts have been extensively studied in terms of their behaviour and characteristics, especially on paraglacial coasts (Carter & Orford, 1984; Jennings & Shulmeister, 2002; Kokot *et al.,* 2005; Orford & Carter, 1995; Orford *et al.,* 1995; Orford *et al.,* 2002). The behaviour of mixed sand and gravel barriers depends on a number of factors including: sediment properties, supply volume and rate, change in sea-level, wave dynamics, tides, site topography, and river discharge (Carter *et al.,* 1989; Forbes *et al.,* 1995; Orford *et* *al.,* 2002). The morphology of these coastlines can rapidly change and fluctuate through a range of states depending on the sediment supply and wave environment. Some barriers are able to migrate, but will only do this if they are free standing away from a backshore cliff (Orford *et al.,* 2002).

Gravel barriers often have associated coastal lagoon systems (Carter & Orford, 1984), and it is evident that these environments require different management compared to lagoons associated with sandy coasts (Orford *et al.,* 2002). Management must take into account the dynamic nature of the environment as well as any tidal influence. Once an outlet channel through a barrier is permanently established, there is an increase in the influence of the tides in the lagoon. If a tidal inlet is not maintained, the barrier may retreat landward and reduce the area of the lagoon (Carter & Orford, 1984).

Hapua generally experience little or no tidal influence, especially when discharge through the outlet is significant (Hart, 2009b; Kirk, 1991). Unlike hapua, which can experience rapid changes in morphology, not all lagoon systems with associated mixed sand and gravel barriers experience rapid changes in morphology (Carter *et al.,* 1989). However, mixed sand and gravel beaches on paraglacial coasts tend to have long periods of slow change in morphology that are interrupted by rapid short term changes (Forbes *et al.,* 1995).

1.2.4 Pressures on coastlines from catchment activities

Activities in river catchments can have a range of impacts on their associated coastlines and marine environment. Catchment dams and an alteration to the flow regime of rivers can have a significant impact on deltas. There have been many studies worldwide on these impacts (Carriquiry & Sánchez, 1999; Ericson *et al.,* 2006; Stanley & Warne, 1998; Yang *et al.,* 2006). These studies have typically focused on large, highly modified rivers such as the Nile, Yangtze and Colorado Rivers. Because river deltas are controlled by fluvial and coastal processes, they are sensitive to dams in their river catchments (Ericson *et al.,* 2006). Deltas are especially vulnerable if the deposition rate of sediment delivered via the fluvial system is less than the rate of sea level rise (Ericson *et al.,* 2006). Many river deltas have changed from a progradational state to an erosional state after dam construction and water abstraction. This is because of the reduction in sediment supply (Stanley & Warne, 1998; Yang *et al.,* 2006). For instance, the Three Gorges Dam has resulted in a recession of the river delta because of the decrease in sediment transported downstream (Yang *et al.,* 2007). Although erosion of the riverbed downstream of the dam has contributed sediment to the river system, the amount has not exceeded the amount trapped behind the dam. As a result, there is an overall sediment deficit at the delta (Yang *et al.,* 2007). A similar effect from abstraction of water for irrigation and a reduction in river discharge has been observed at the Colorado River delta (Carriquiry & Sánchez, 1999).

The change in sediment transport, especially fine sediment, down rivers can impact beaches along the coast. Although sediment can be regenerated from the floodplain downstream of dams (Kondolf, 1997; Young *et al.,* 2004), many coastlines have been impacted by a decrease in sediment supply. Sources of sediment for beaches can come from: rivers, the erosion of coastal cliffs, longshore drift, and sediment transported from the near shore seabed via cross-shore transport (Velegrakis *et al.,* 2008). Dams are considered to have the greatest impact on beach stability due to their impact on sediment transport. A reduction in fine sediment post dam development has been linked to the significant coastal erosion along the coastlines of the northeast Bohai Sea, as well as at the mouths of a number of rivers in the area (Xue *et al.,* 2009). It has been well documented that the preservation of beaches in California depends on input of bedload and suspended sediment from river catchments. The replenishment of many beaches in California has been reduced because of the obstruction of sediment by barriers in the river catchments and also from a decrease in river discharge due to water abstraction (Willis & Griggs, 2003). It is evident that dams are often a major contributor to coastal erosion, although it is often difficult to isolate other interacting factors and determine the degree of influence.

Although dams can impact the coast, similar effects can often arise due to other natural and anthropogenic factors occurring in the river. The relative impacts of these factors are often difficult to differentiate from each other. Sediment loadings may naturally decrease as a result of climate change induced alteration in river flow regimes. Anthropogenic alterations to the transport of sediment to the coast can include sediment mining, the construction of dykes, and man made structures such as jetties (Sherwood *et al.,* 1990). Water abstraction, which often occurs in combination with dam construction, can have additional adverse impacts on sediment transport if the sediment transporting flow is reduced (Hicks, 2011; Sherwood *et al.,* 1990). These factors are often difficult or impossible to separate from each other, making the exact cause of the observed change in sediment transport to the coastal environment, or the amount of influence that each factor is having on sediment in the river difficult to determine.

Coastal and marine biota can be indirectly affected by changes that occur in river catchments. The reduction in sediment supply to the coastal environment can have detrimental impacts on coastal wetlands and habitat available for intertidal species, as is the case of the Yangtze River delta and the Skokomish River respectively (Yang *et al.,* 2006). Water diversion from the Donets and Kuban Rivers has been linked to a 90-95% decrease in the catch rates of anadromous fish, along with the loss of 50-80% of fish habitat (Jay & Simenstad, 1996). With a decrease in suspended sediment, the increase in light penetration through the water can affect aquatic biota (Collier *et al.,* 1996).

Changes in nutrient dynamics such as those that have occurred off the coast of the Skokomish River, is a common phenomenon post dam construction or with an increase in water abstraction (Jay & Simenstad, 1996). Dams have been linked to a decrease in dissolved silica in the coastal environment. This, in combination with an alteration in nutrient concentrations, has lead to a change in the proportion of diatoms and dinoflagllates in the Black Sea (Humborg *et al.,* 2000). Changes to dissolved silica in the marine environment, as well as a change in water temperature due to changes in fluvial flow regime have the potential to alter entire food webs (Fan & Huang, 2008; Humborg *et al.,* 2000).

1.3 Research context

1.3.1 Water storage in the Hurunui Catchment

Water storage in the Hurunui catchment is needed not only for economic growth, but also to stabilise irrigation supply as the river currently experiences low flows during the summer months (Boffa Miskell Limited, 2011). There are a number of proposals for water development on a number of rivers in the Hurunui Region (Hurunui District Council & Canterbury Water, 2010; Waitohi Selection Panel, 2011). Initially, the main focus for dam development was for the Hurunui River, but has recently shifted to the Waitohi River. The initial Hurunui River proposal was for water storage on the Hurunui River, either on the distribution canal downstream of the Mandamus River confluence where water would be diverted from the river, in a the dam in the South Branch of the Hurunui River, or both (Figure 1.2) (Hurunui District Council & Canterbury Water, 2010). The PHWRRP (Proposed Hurunui-Waiau River Regional Plan) Policy 6.1 states that there are to be no dams on the mainstem of the Hurunui River (Environment Canterbury, 2011g). To avoid this, one of the dams was proposed for the South Branch of the upper Hurunui River which is not considered to be on the mainstem of the river. Water was proposed to harvested from the Hurunui River downstream of the Mandamus River confluence and upstream of the Dampier Stream confluence (Hurunui District Council & Canterbury Water, 2010).

A 3 m weir was proposed for the outlet of Lake Sumner, as well as a 75 m dam in the South Branch of the Hurunui River (Hurunui District Council & Canterbury Water, 2010). The storage in Lake Sumner would be approximately 27 million m^3, and 111 million m^3 in the South Branch dam (Hurunui District Council & Canterbury Water, 2010). The top meter of the weir at the Lake Sumner outlet would be used to control flood inflows (Ward & Veendrick, 2009). Under the Hurunui River proposal, it was expected that the two dams (Lake Sumner and the South Branch dam), in combination with a series of water races would service water to approximately 42,180 ha of land (Hurunui District Council & Canterbury Water, 2010).

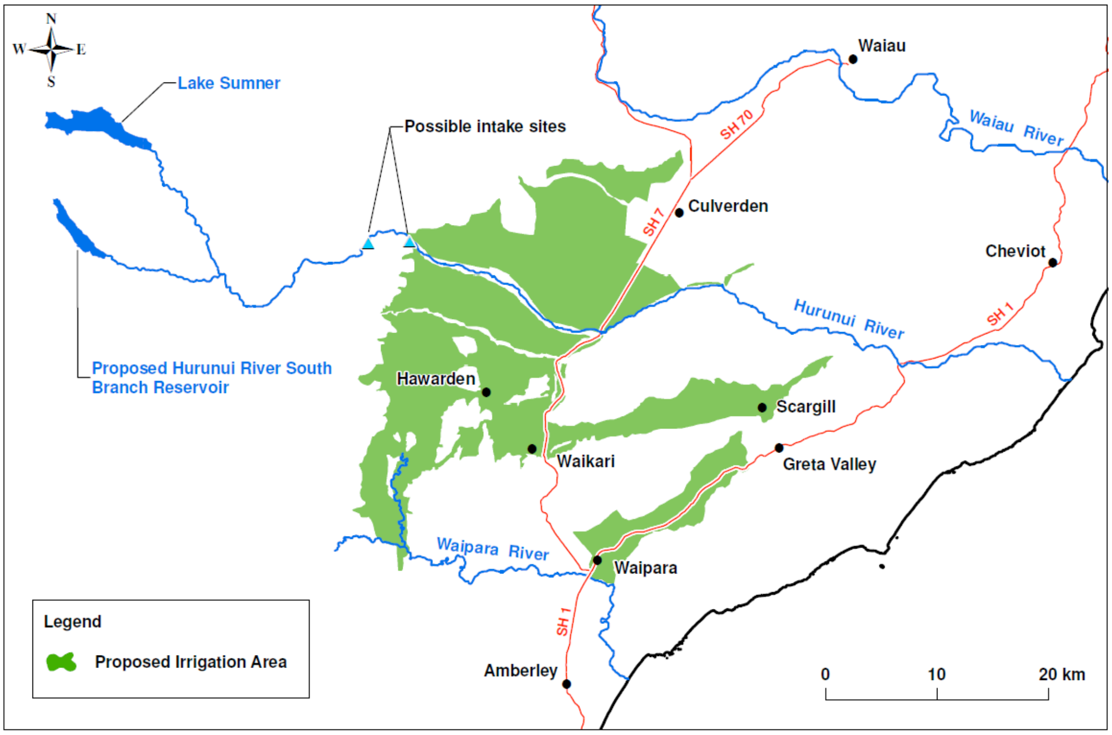


Figure 1.2: Proposed irrigation area of the Hurunui Water Project and the location of the Hurunui River and other major rivers in the Hurunui River catchment (Hurunui Water Project 2012).

The preferred option for water storage in the Hurunui Region is now on the Waitohi River (Figure 1.3). The resource consent application for the Waitohi River proposal was notified on the 8th of September 2012 by Environment Canterbury (Environment Canterbury, 2012c). It is proposed that when water availability is too low to abstract from the Hurunui River, stored water in the 4 proposed dams on the Waitohi River would be released (Chris Hansen Consultants Limited, 2012; Environment Canterbury, 2012c). This proposal includes intake 1 and 4 on the Hurunui River, intake 3 which is part of the Amuri scheme, and intake 2 on the Waitohi River (Chris Hansen Consultants Limited, 2012). The 4 dams would be located at Hurricane Gully (which would be fed by pumped water from the Hurunui River), Seven Hills, Inches Road and in the Lower Gorge (Environment Canterbury, 2012c).

The proposed Hurricane Gully dam on the Waitohi River would be 105 m high and 429 m wide, the Seven Hills dam 46 m high and 150 m wide, the Inches Road dam 31 m high and 245 m wide, and the Lower Gorge dam 20 m high and 70 m wide (Chris Hansen Consultants Limited, 2012). The combined storage of the Lower Gorge, Seven Hills, and Inches Road dams would be 19.7 million m^3 and the storage of the Hurricane Gully dam would be 227.2

million m^3 (Christensen & Torgerson, 2012). If the HWP proposal for the Waitohi River were approved, up to 58,500 ha of land in the Hurunui, Waipara, and Kowai catchments would be serviced by water from this irrigation network (Waitohi Selection Panel, 2011).

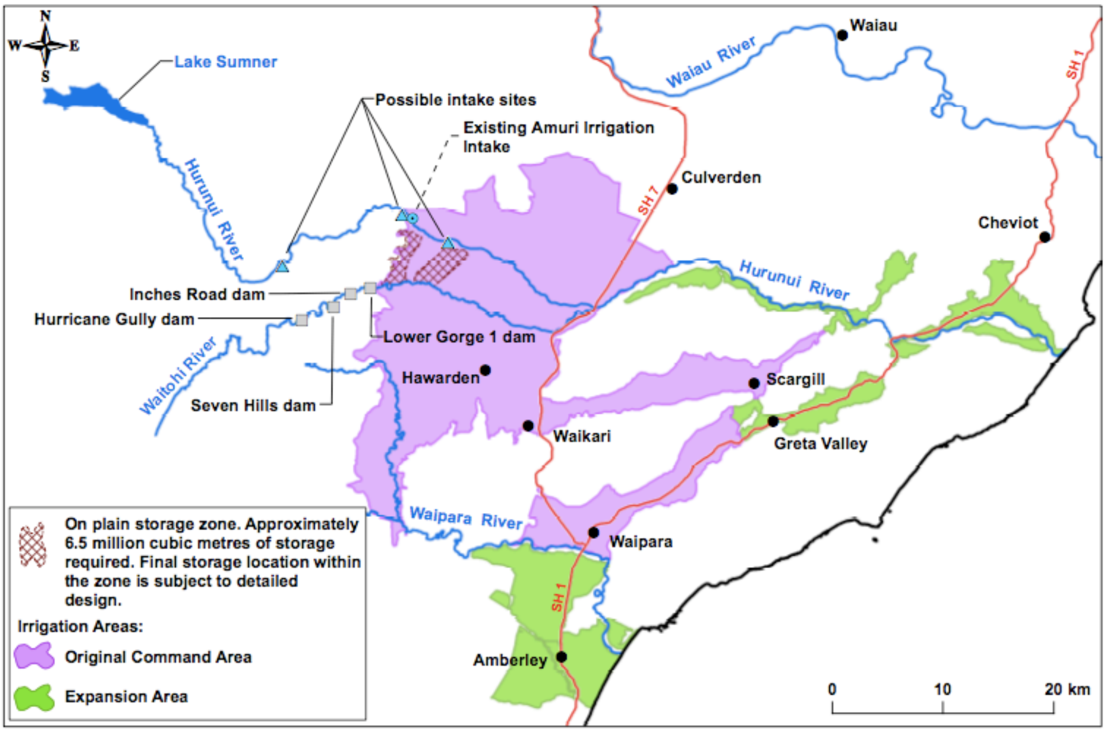


Figure 1.3: Proposed irrigation area of the water development on the Waitohi River and the location of other major rivers in the Hurunui District (Hurunui Water Project 2012).

Overall, the Hurunui-Waiau Zone Committee favours the Waitohi River option that is proposed by the Hurunui Water Project (HWP) (Canterbury Water *et al.,* 2011). Since October 2011, two years have been designated to determine the viability of this option. If this is found to be unviable, the South Branch dam option will be further explored. A dam in the South Branch of the Hurunui River is identified by the zone committee as the most economically viable option compared to the Lake Sumner option. However, significant environmental and recreational impacts associated with this option still remain (Canterbury Water *et al.,* 2011).

1.3.2 Potential effects of the dam proposals

The HWP has commissioned a number of companies to conduct environmental assessments to determine the possible and likely impacts of the proposed irrigation schemes in the Hurunui River catchment. The potential impacts may involve: hydrological regime, sediment processes, ecology, and hapua dynamics and processes (Table 1.1). The details of these potential effects are outlined in Appendix 1.

The hydrological regime is likely to change under both the Hurunui and Waitohi River proposals. The reduction in flood frequency and magnitude is expected to be less under the Waitohi River proposal (Veendrick, Pennington, & Brunton, 2012). It is expected that there would be a reduction in baseflows at the river mouth under both of the proposals due to the abstraction of water upstream (Christensen & Torgerson, 2012; Lin, 2009; Mosley & Environment Canterbury, 2004). The change in hydrological regime would alter sediment transport, although the effect under the Waitohi River proposal is expected to be less due to a sediment-flushing regime (Christensen & Torgerson, 2012).

Table 1.1: Potential effects of the Hurunui and Waitohi dam proposals on the Hurunui River and river mouth.

	Hurunui proposal – river effects	**Waitohi proposal – river effects**	**River mouth**
Hydrological regime	↑ flow variability, ↑ baseflow during irrigation season ↓ flood frequency and magnitude	↓ baseflow, ↓ flood frequency, ↓ flood magnitude	↓ baseflow, ↓ flood frequency, ↓ flood magnitude
Sediment processes	↓ sediment transport	↓ sediment transport	↓ sediment transport
Ecology	↑ periphyton flushing during summer, ↓ habitat for flora and fauna, ↓ fish passage	↓ habitat for flora and fauna, ↓ fish passage	unknown

1.4 Research gap and objectives

Although hapua processes and dynamics, especially with regard to geomorphology, are relatively well understood, there are still a number of unknowns. It is assumed that river flow variations are a key factor in changes in the health of hapua (Whitehouse *et al.,* 2011). This does not take into account other interacting factors such as coastal processes. There are many types of catchment effects that can degrade river mouths. For instance, agricultural and industrial development often increases nutrient concentrations, altering food webs and resulting in an increase in the incidence of algal blooms (Fan & Huang, 2008; Humborg *et al.,* 2000; Jay & Simenstad, 1996). Developments in river catchments such as dams and water abstraction and activities such as sediment dredging (Hicks, 2011; Sherwood *et al.,* 1990) can trap sediment, leading to, or increasing coastal erosion (Stanley & Warne, 1998; Yang *et al.,* 2006). Catchment changes can also adversely impact biota as sediment loadings and flow regimes change, and the morphology is altered (Collier *et al.,* 1996; Jay & Simenstad, 1996; Ligon *et al.,* 1995). To adequately understand the role of catchment processes on the health and behaviour of coastal lagoons, baseline information on a range of processes must be known, and this information is currently largely lacking for the Hurunui River hapua.

It is assumed that the flows set in the Hurunui Waiau Regional Plan are sufficient at maintaining hapua health (Whitehouse *et al.,* 2011). There are two issues with this approach, firstly, as stated by Whitehouse *et al.* (2011), the health of the hapua is currently in a state of decline, although it is acknowledged that the current state of the hapua is largely unknown. Therefore if the set flows are sufficient in maintaining the current state of hapua health, there will continue to be a decline in health in the lower river (Ausseil, 2010; Hayward, 2001).

The majority of the studies that have examined the potential impacts of the proposed dams in the Hurunui Catchment have focused on the immediate river and Lake Sumner. Only a select few have mentioned the possible effects at the river mouth, and most of the predictions have been inconsistent, especially with regard to the change in sediment loads and coastal erosion. These environmental impact assessments have largely failed to take into account the effects of the catchment on the hapua, and how the changes could impact on the health and behaviour of the lagoon. Also, prolonged low flows and an elongated offset have the potential to degrade water quality due to a longer residence time of water within the lagoon (Kirk, 1991). Even if the hapua has an open outlet, the health of the hapua is not always satisfactory. Although a number of rivers with associated hapua in New Zealand have altered and controlled flow regimes due to dams in their catchments, there is a lack of research on the effects of these catchment changes on the associated hapua (Hart & Bryan, 2008). In order to adequately understand the effect of dams on coastal lagoons, it is vital that there be studies of the hapua before the dams are constructed. Hart (2008) highlights the urgent need for a more in-depth scientific understanding of the link between fluvial and coastal systems on mixed sand and gravel coasts where hapua occur.

Although the Hurunui River is not in its 'natural' state with regard to flow regime due to water abstraction, there is the opportunity to understand the present cycles and behaviour of the hapua so that the effects of damming and/or increased water abstraction can be understood more. There is virtually no information on the biota and the physico-chemical characteristics of the water in hapua in New Zealand and how these aspects respond to change. This knowledge is important not only for the post dam or catchment change impacts to be determined, but for the appropriate management of hapua.

Arising from this literature review, **the overall purpose of this thesis is to examine the current conditions and how it responds to the observed range of contemporary catchment and coastal processes, and longer-term behaviour of the Hurunui River hapua. The purpose of this is to collect the data that will assist in future evaluations of dam impacts and associated catchment change on the Hurunui River hapua.** The aim is to contribute to the existing information with regard to natural cycles of change in hapua geomorphology and behaviour, and the baseline sediment processes and water physico-chemical characteristics throughout the hapua under different conditions.

This aim can be separated into several distinct objectives:

1. to examine and quantify the suspended sediment, water quality, and nutrient characteristics existing in different areas of the Hurunui hapua, under different energy conditions, and at different stages of the tide;

2. to examine substrate composition in different areas of the Hurunui hapua;

3. to determine where the majority of the sediment is currently transported, deposited and transferred to within the Hurunui hapua system;

4. to understand the geomorphic dynamics of the Hurunui hapua, including short-term (daily, event) and longer-term (decadal) cycles in Hurunui hapua behaviour, areal

extent, shoreline position, and barrier width; and

5. to use investigation of monthly to annual trends in hydrology, nutrient concentrations, and other water quality parameters in the lower Hurunui River, and in significant wave height and direction along the Canterbury Coast in order to understand how the hapua system responds to these process agents.

1.5 Thesis outline

This chapter has presented the purpose and objectives of this research arising from the context of the literature on hapua and the effects of dams worldwide. An outline of the dam proposals in the Hurunui District was given. Gaps in the knowledge and literature on hapua and the effects of catchment activities were identified.

Chapter 2 gives details on the Hurunui River and the study site. It also outlines the overarching methodologies of this study. This includes details on the methodologies of worldwide coastal lagoon studies, and the approach used in this study. It also includes considerations that have to be taken into account at the study site, such as safety.

The subsequent four chapters outline the methods and results from the baseline studies. This includes recent hydrological and wave data, and results of sediment processes, water quality parameters, and nutrients in the hapua.

Chapter 7 outlines the short term and historical changes in the hapua behaviour and morphology. In particular, this includes an analysis of long-term changes in the hapua area and shoreline.

Chapter 8 is dedicated to an integrated discussion of the results. The discussion of the potential impacts of the proposed dams on the river mouth is reserved for this chapter.

Finally, the main findings of this study are summarised in Chapter 9, along with suggestions for further research.

Chapter 2: Study site and methodology

2.1 Introduction

This chapter gives details of the study site. It also outlines the overarching methodologies of this study. The main approaches and the reasons for them are discussed. The details of the specific methods are reserved for the following chapters. These details include: principles and practices of the various methods, methods that were used in this study, how the data was collected, how the samples and data were processed, and any limitations and errors.

This chapter describes the Hurunui River catchment in section 2.2. It outlines the different approaches that have been used to study coastal lagoons in section 2.3. Following this is the methodology approach used in this study in section 2.4 which includes both short-term baseline information and long-term information using aerial photographs. This section also includes safety considerations of this study site. This chapter concludes with a summary in section 2.5.

2.2 Study site

2.2.1 Catchment and river characteristics

The Hurunui catchment is located in North Canterbury (Figure 2.1) and includes the 150 km long Hurunui River, the Waitohi River, and a number of smaller rivers (Seaward, Mandamus, Waitohi, and Pahau Rivers) that flow into the Hurunui River (McLintock, 2009). The Hurunui River catchment is approximately 2680 km^2 with the upper catchment above the Mandamus River confluence consisting of 39% of the total area, and the lower catchment 61% of the total area (Bowden, 1977). The Hurunui River is bordered by four major catchments: the Waimakariri, Ashley and Waipara River catchments to the south, and the Waiau River catchment to the north (Figure 2.2) (Bowden, 1977; Environment Canterbury, 2011b; Griffiths & Glasby, 1985). A number of smaller catchments border the lower section of the

Hurunui River, and these include: Motunau, Boundary Creek, Blyth River, Port Robinson and Jed River catchments (Environment Canterbury, 2011b).

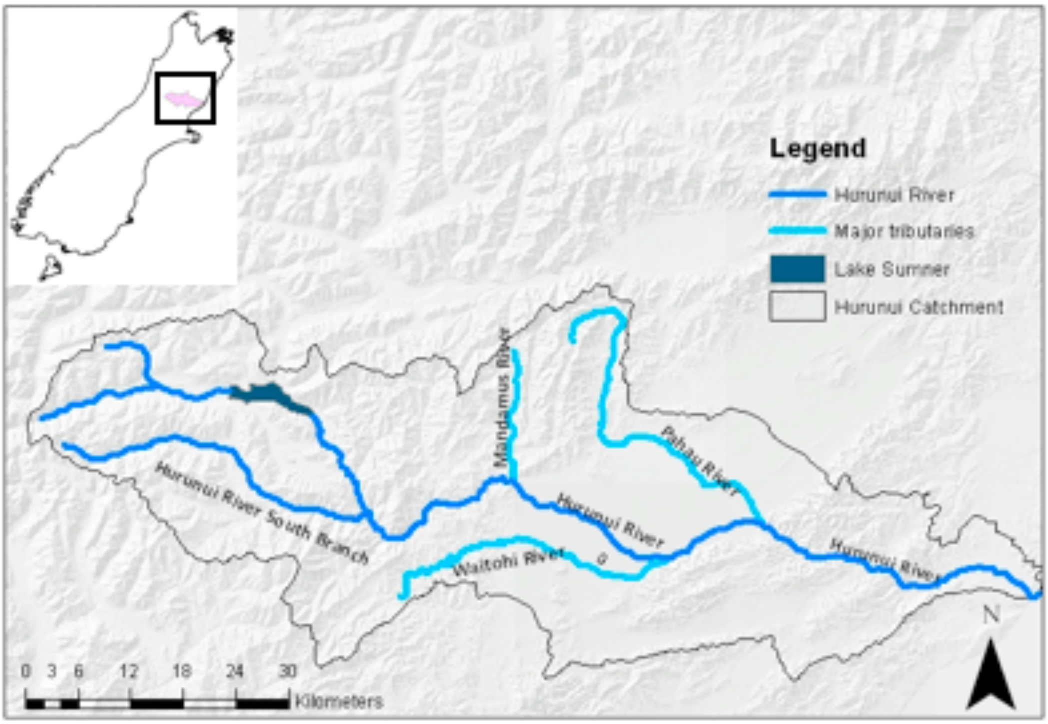


Figure 2.1: Location of the Hurunui Catchment, the Hurunui River, and its major tributaries.

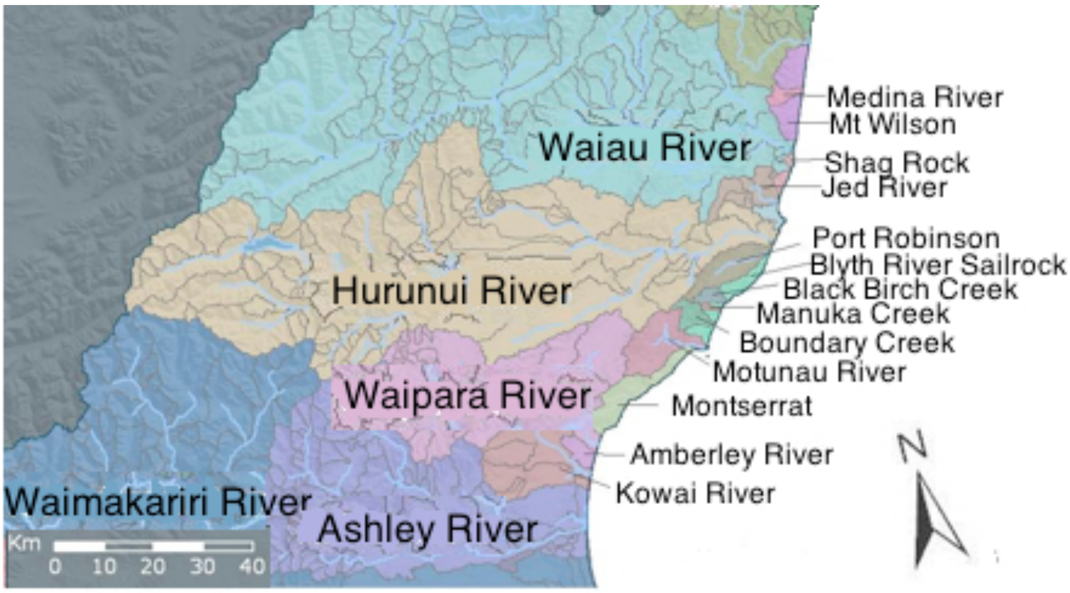


Figure 2.2: Hurunui River catchment and surrounding catchments in the North Canterbury Region (Environment Canterbury, 2011b).

The mainstem of the Hurunui River originates on the eastern side of the Southern Alps as a mountain stream in steep bush-covered slopes just below Harper Pass, also known as the Hurunui Saddle (Egarr *et al.,* 1981; McRae, 1993). After entering Lake Sumner, it exits as the North Branch. The South Branch originates between the Crawford and Studleigh ranges and merges with the North Branch downstream of Lake Sumner (Egarr *et al.,* 1981; McRae, 1993).

The Hurunui River has a range of different sections along its length based on scenic and recreational values that vary in morphology and length (Table 2.1 and Figure 2.3). These range from gorges to braided plains (Bowden, 1977; McRae, 1993; Roper-Lindsay & Environment Canterbury, 1991). After the Hurunui River exits Lake Sumner, it flows through a gorge before reaching the Amuri and Culverden Plains (Egarr *et al.,* 1981; McRae, 1993). These plains are located between the Main Divide and the coastal hills and have been formed by broad coalescing glacial outwash fans, as well as from gravel that has been deposited by the Hurunui River. The river flows through two more gorges before reaching the sea south of Gore Bay and 80 km north of Christchurch (Bowden, 1977; McRae, 1993).

Table 2.1: Sections of the Hurunui River (adapted from Bowden, 1977 and Egarr, 1981).

Section name	Location	Length	Description
Upper Hurunui and Lakes	East side of Harper Pass to Lake Sumner	37km (including the lake)	Is initially a rocky stream and later as a fine gravel bed stream before entering the lake
Lake Sumner to South Branch	Lake Sumner to junction with the South Branch	17km	River flows through two short gorges, divided by a boulder bed section with pools
South Branch	East of the Main Divide to the North Branch	44km	Shallow shingle bed
Maori Gully and Hawarden Gorge	Confluence of the two branches to the Culverden Plains	25km	Flows gently over a shingle bed before entering Maori Gully where rapids are present, ending in braided shingle flats. Flat land is scarce.
Middle Hurunui River	Mandamus River confluence to the Lowry Peaks Gorge	36km	Braided section flowing through the Amuri Plains
Lowry Peaks Gorge	From the Lowry Peaks Range to he coastal plain south of Cheviot	20km	Gentle lowing over a shingle bed
Lower Hurunui River	From SH1 to the sea	19km	Braided river over wide shingle bed. Rolling hills

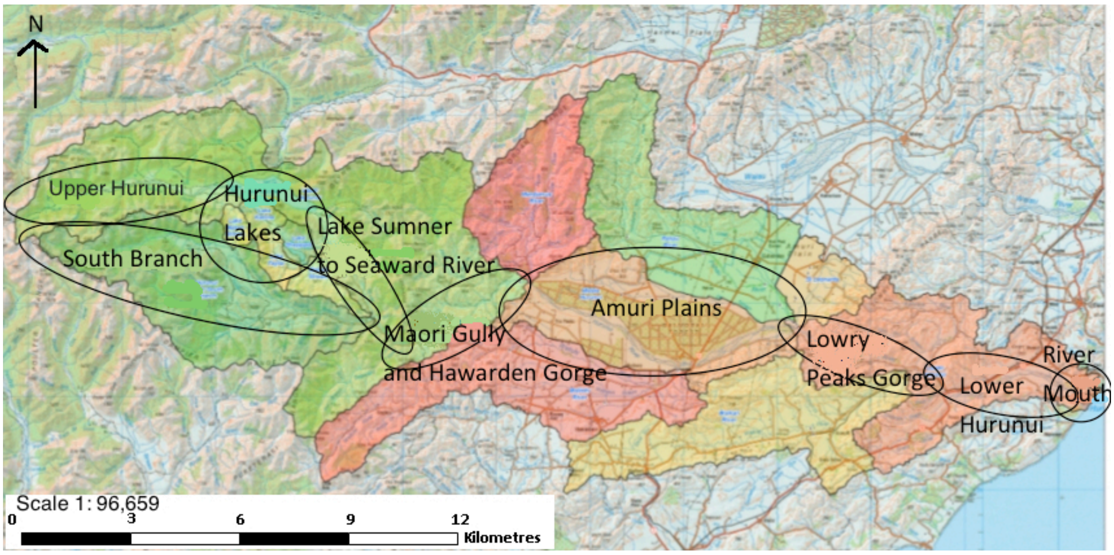


Figure 2.3: Location of the major sections of the Hurunui River (Environment Canterbury, 2011d).

As well as the Hurunui River being divided into sections based on recreational and scenic values, it has also been divided according to landscape types. Of the 10 landscape types for the Hurunui District identified by Lucas Associates (1995), 8 are found along the Hurunui River. These landscape types include:

- main divide landscape (at the headwaters),
- major river valley (mainstem and South Branch),
- mountain range (at Maori Gully),
- hard rock hill landscape (at Hawarden gorge, Lowry Peaks Range and below the soft rock downland landscape),
- inland basin floor (Amuri Plain),
- soft rock downland landscape (downstream of Lowry Peaks Gorge),
- plains landscape (below the hard rock hills landscape in the lower reach of the river),
- coastal hills landscape (at the end of the river).

The Waitohi River originates south east of the Hurunui River and east of the Puketeraki Range (Egarr *et al.,* 1981). The headwater of the Waitohi River is approximately 1300 m in elevation and is approximately 190 m in elevation at the point at which it converges with the Hurunui River. This catchment is approximately 320 km^2 and the river is 59 km long (Egarr *et al.,* 1981; National Institute of Water and Atmospheric Research, NIWA, 2007).

The Waitohi River has different characteristics to the Hurunui River. The upper section of the Waitohi River is meandering and marshy and narrows at Seven Hills before flowing into the Hurunui River at the Culverden Plain. This river experiences lower flows compared to the Hurunui River, and during the summer the flow is so low that it frequently almost dries up (Egarr *et al.,* 1981).

2.2.2 Rainfall and temperature

The Hurunui River catchment consists of three hydrological regions, and these include the Eastern Alps, the Hurunui, and the Canterbury Plains (Bowden, 1977). The Eastern Alps region experiences the highest rainfall while the Canterbury Plains region experiences the lowest rainfall and runoff due to dominant westerlies. The upper catchment has a mean annual rainfall of around 5000 mm compared to 622 mm on the Amuri Plain (Bowden, 1977). The lowest river flow is during the summer when evapo-transpiration is the highest and rainfall at its lowest (Figure 2. 4), and the highest flows occur from September to November (Figure 2.5) (Mosley, 2002). Summer and winter rainfall is expected to reduce, while summer and winter temperatures are expected to increase with climate change (Bell, 2001). Temperatures are high on the Amuri Plain during the summer and cold with frosts in the winter (Figure 2.4).

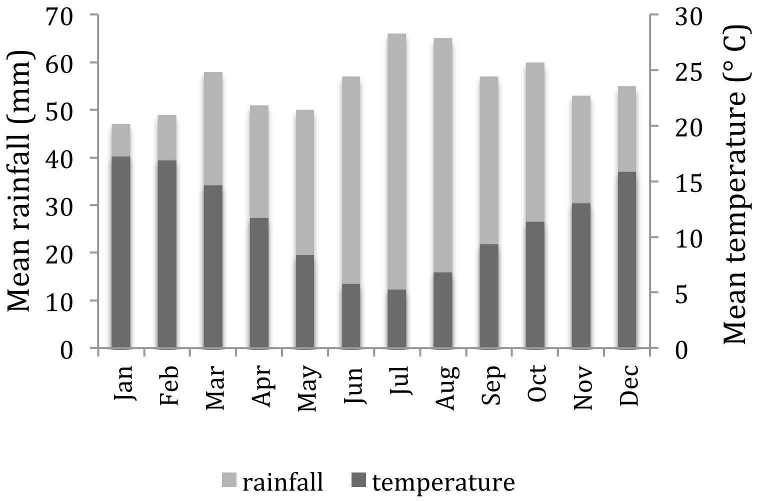


Figure 2.4: Mean monthly rainfall (mm) based on NIWA data from 1972 to 2008, and mean monthly air temperature (°C) based on NIWA data from 1983 to 2009 from the Culverden climate station (Ward & Veendrick, 2009, p.8).

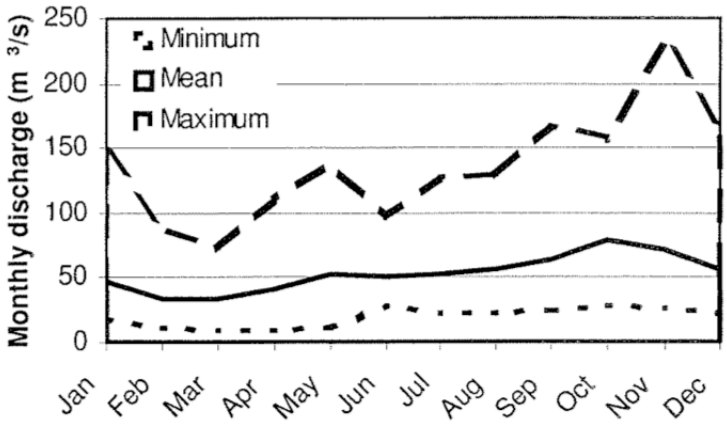


Figure 2.5: Monthly, minimum, and maximum flows from 1957 to 2000 at the Mandamus recorder in the upper Hurunui River (Mosley, 2002, p.46).

2.2.3 Land cover

The majority of the soils in the Hurunui catchment are Balmoral, Glasnevin and Culverden silt and sandy loams (Chris Hansen Consultants Limited, 2011). The majority of the rocks in the Hurunui River catchment are greywacke and argillite of the Torlesse Group. The plains and river valleys are overlain with glacial outwash gravels, terrace deposits and river aggradation gravels (Bowden, 1977).

Land use has a major influence on the health of waterways and agriculture can have particularly negative impacts on erosion and nutrient runoff (Foley *et al.,* 2005; Milliman & Farnsworth, 2011). The majority of the land use in the Waitohi and Hurunui catchments used to be dry grass and shrubland used for sheep and beef farming, with a number of forestry plantations on the Amuri Plain (Brown *et al.,* 2011; McRae, 1993; Roper-Lindsay & Environment Canterbury, 1991). The upper Hurunui catchment has a range of vegetation, from native beech forest (*Nothofagus* spp.), alpine snow tussock and tussock grassland, to exotic plantations and scrub (Keye *et al.,* 2011). The Waitohi headwater is mostly steep grazing land with tussock and matagouri (Egarr *et al.,* 1981). Recently, with the increase in irrigation, dairying has intensified on the flat land in the Culverden Basin (Brown *et al.,* 2011). Dairying has increased significantly since the 1980s, so irrigated pasture for dairying is now the major land use on the Culverden Basin. Provided irrigation is possible, it is expected that agriculture, in particular dairy farming, will continue to intensify (Brown *et al.,* 2011).

2.2.4 Water quality

The upper section of the Hurunui River is largely in its natural state, but the lower reaches have been significantly modified from their natural state by anthropogenic activities. There is a general downward trend in water quality downstream (Mosley, 2002).

The tributaries, including the Waitohi River, that flow into the Hurunui River originate in the mountains, foothills and plains (Roper-Lindsay & Environment Canterbury, 1991). The majority of these tributaries are in poor health, and this decline in health is likely to continue with the expected intensification of agriculture and irrigation (Whitehouse *et al.,* 2011).

There is a gap in the knowledge on biota and the ecology in the Hurunui River hapua. Hapua have been identified as an important habitat for migrating fish such as Chinook Salmon, Brown Trout, and Rainbow Trout (Mosley, 2002). Longfinned and shortfinned eels, as well as whitebait also pass through the river mouth. The Hurunui River mouth is also important for native and introduced bird species. Species include banded dotterel, black-fronted tern (Armstrong, 2006). Currently, there is no information on the aquatic vegetation and invertebrates at the Hurunui River mouth. During the course of this study, the growth of different forms of periphyton was observed. These included filamentous algae, cyanobacteria mats, and thin films (Figure 2.6).

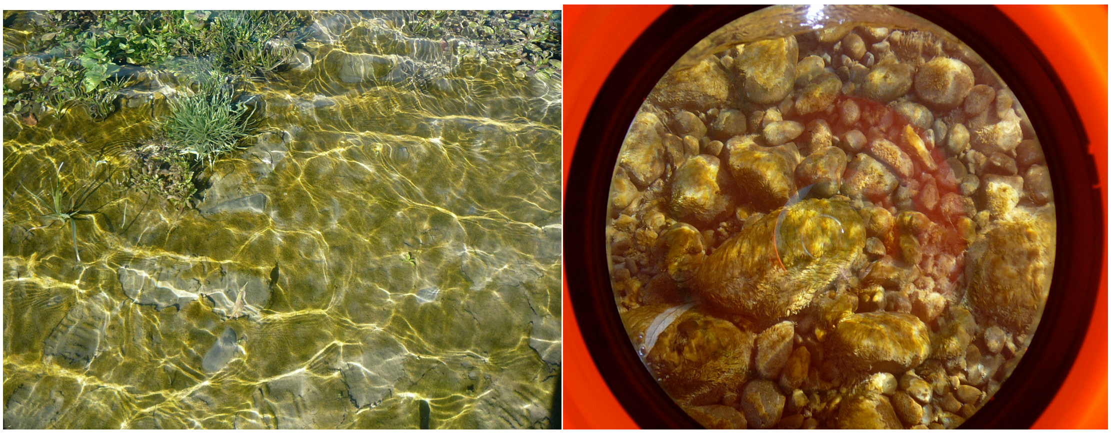


Figure 2.6: Photographs of cyanobacteria mats (left), and filamentous algae (right) at the Hurunui River hapua.

2.2.5 River management framework

There has been a long history with regard to dam proposals on the Hurunui River. The suitability of this river for hydroelectricity generation has been identified as early as 1904 (Bowden, 1977). Proposals to develop a hydroelectric dam occurred as far back as the 1960s when there was an acute electricity shortage in the South Island. In response to the need for water for farming on the naturally dry Amuri Plain, the Balmoral Irrigation scheme was developed (McRae, 1993). This involved a primitive scheme where a series of irrigation races drained from a swamp at Sanford Downs, which then fed to the surrounding farmland (McRae, 1993). Later on due to increased demand, the government agreed to finance a new improved scheme in 1981, with water flowing out of the Hurunui in 1984 just below the Mandamus River confluence, and feeding into a network of irrigation races (McRae, 1993; New Zealand Fish and Game Council *et al.,* 2010). This scheme is currently managed by the Amuri Water Company Limited and irrigates 5,234 ha (Abraham & Hanson, 2006; New Zealand Fish and Game Council *et al.,* 2010). As well as the Balmoral Irrigation Scheme, there are currently a number of other irrigation schemes in the Hurunui River catchment. These include: the Waiau, David Rutherford and Waireka Downs Irrigation Schemes which are sourced from the Waiau River, and the Hassall-Zino Irrigation Scheme which is sourced from the Hurunui River (Abraham & Hanson, 2006).

In 2009, the New Zealand Fish and Game Council, the New Zealand Recreational Canoeing Association, and the North Canterbury Fish and Game Council applied for a water conservation order for the Hurunui River (Hurunui District Council & Canterbury Water, 2010). This was done with the intent to preserve the outstanding characteristics for fishing and kayaking, as well as the cultural, natural and scenic values particularly in the upper catchment, but also in the lower river (New Zealand Fish and Game Council *et al.,* 2010). However, the application for the water conservation order for this river was withdrawn at the end of 2010 (Environment Canterbury, 2011e).

A moratorium was placed on the Hurunui River and its tributaries by Environment Canterbury from 2 August 2010 until 1 October 2011 to enable a suitable water management plan to be developed for the Hurunui River catchment (Environment Canterbury, 2011h).

The Hurunui Community Water Development Project was formed in 2002 initially as a working group, and later changed name to the Hurunui Water Development Project (HWP) (Hurunui Water Project, 2010; Lin, 2009; Ward & Veendrick, 2009). The Hurunui Water Project consists of Enterprise North Canterbury, Hurunui Irrigation and Power Trust, Ngai Tahu, Mainpower, and David Teece the owner of Eskhead Station (Hurunui District Council & Canterbury Water, 2010; Hurunui Water Project, 2010). The HWP was formed in response to the growing water demand in the district, with the purpose to explore various ways in which to develop a water storage scheme whilst ensuring agricultural and environmental sustainability in the Hurunui-Waiau Region (Lin, 2009; Ward & Veendrick, 2009). The vision of the HWP is to:

> *"Identify and promote a combination of water management regimes and water storage options that collectively enhance the sustainable management o in-river flows within the Hurunui District within an environmentally sensitive, consentable and viable scheme, while providing for the irrigation, hydro-generation and economic needs of the Hurunui District"* (Hurunui Water Project Limited, 2010, p.4).

The HWP must work in accordance with the Canterbury Water Management Strategy (CWMS) which was formed between 2004 and 2010 with the intent of managing water resources in the Canterbury Region in a environmentally sustainable manner (Environment Canterbury, 2011g), the aim of which is to:

> *"To enable present and future generations to gain the greatest social, economic, recreational and cultural benefits from our water resources within an environmentally sustainable framework"* (Hurunui District Council & Canterbury Water, 2010, p.20).

Targets have been set for the years 2015, 2020, and 2040 to ensure that the aims of the CWMS are being met (Hurunui District Council & Canterbury Water, 2010). These targets include the following aspects: ecosystem health/biodiversity, natural character of braided rivers, Kaitiakitanga, drinking water, recreational and amenity opportunities, water-use efficiency, irrigated land area, energy security and efficiency, regional and national economies, environmental limits (Hurunui District Council & Canterbury Water, 2010).

The CWMS is divided up into 10 zones, each with its own committee as well as a regional committee (Environment Canterbury, 2011g). Zone Water Management Committees are composed of various interest groups (Environment Canterbury, 2011f). For instance, the Hurunui Waiau Water Management Zone Committee, which was formed in 2010, consists of the Hurunui District Council, Environment Canterbury, and others. Other members of this committee include Rūnanga representatives, and 7 local representatives who exhibit a range of expertise and interests. An informal recommendation of the committee is that the members can only be on a committee for 3 years (Environment Canterbury, 2011f). Firstly, the Hurunui Waiau Water Management Zone Committee consulted a wide variety of interested groups including: scientists, Rūnanga, local communities, and governmental and non-governmental organizations (Canterbury Water *et al.,* 2011). After this consultation, the committee was responsible for developing and reviewing the Zone Implementation Programme (ZIP), as well as being responsible for managing local resources in an environmentally sustainable manner (Environment Canterbury, 2011g; Hurunui District Council & Canterbury Water, 2010). The goal of the ZIP is to:

> *"Recommend actions and approaches for integrated water management solutions in order to achieve the Canterbury Water Management Strategy principles, targets and goals encompassing economic, social, cultural and environmental outcomes"* (Canterbury Water *et al.,* 2011, p.5)

Since September 2011, Environment Canterbury and the Hurunui District Council have implemented the recommendations in the ZIP, of which are in accordance with the CWMS principles, targets and goals (Canterbury Water *et al.,* 2011). The Hurunui-Waiau Water Management Zone Committee expects these recommendations to be integrated into the Hurunui Waiau Regional Plan so that the CWMS targets are met and that water resources in the Hurunui-Waiau Region are managed sustainably and continue to be protected (Canterbury Water *et al.,* 2011; Environment Canterbury, 2011g). Any proposal for water development in the Hurunui River, and the recommendations for water management by the ZIP must be in accordance with the CWMS principles and outcomes (Canterbury Water *et al.,* 2011).

Overall, this framework has been developed to ensure water availability for agricultural and horticultural development as well as the associated social and economic prosperity in a way that is environmentally and culturally sensible (Canterbury Water *et al.,* 2011; Environment Canterbury, 2011g). It is evident that there must be a careful balance between water abstraction for agricultural and economic prosperity and the cost to the environment, especially with regard to water quality.

2.2.6 Coastal management framework

A management framework has been developed for the coastal environment (Figure 2.7). The Regional Coastal Environment Plan for the Canterbury Region has been developed under the directions of and in accordance with the New Zealand Coastal Policy Statement to ensure the protection, sustainability and improvement of the coastal environment and the Coastal Marine area in the Canterbury Region (Environment Canterbury, 2005). This includes the management of both natural and physical resources. In particular, focus is placed on:

> *"Protection and enhancement of the coast; water quality; controls on activities and structures; and coastal hazards" (Environment Canterbury, 2005, p.1-2).*

This statement is vague, especially with regard to the enhancement of the coast. This could be interpreted in many different ways. For instance, enhancement could be seen as the use of the coastal environment for recreational and living purposes, while others may see it as enhancing the coastal environment by leaving in its natural state.

The area that this plan covers is from 12 nautical miles offshore to the Mean High Water Springs (Environment Canterbury, 2005). This plan takes into account the issues that are prevalent at the land/water interface and includes the Hurunui River mouth. This river mouth has been identified as having high value for: marine mammals and birds, ecosystems, flora and fauna habitats, and coastal landforms and their associated processes (Environment Canterbury, 2005).

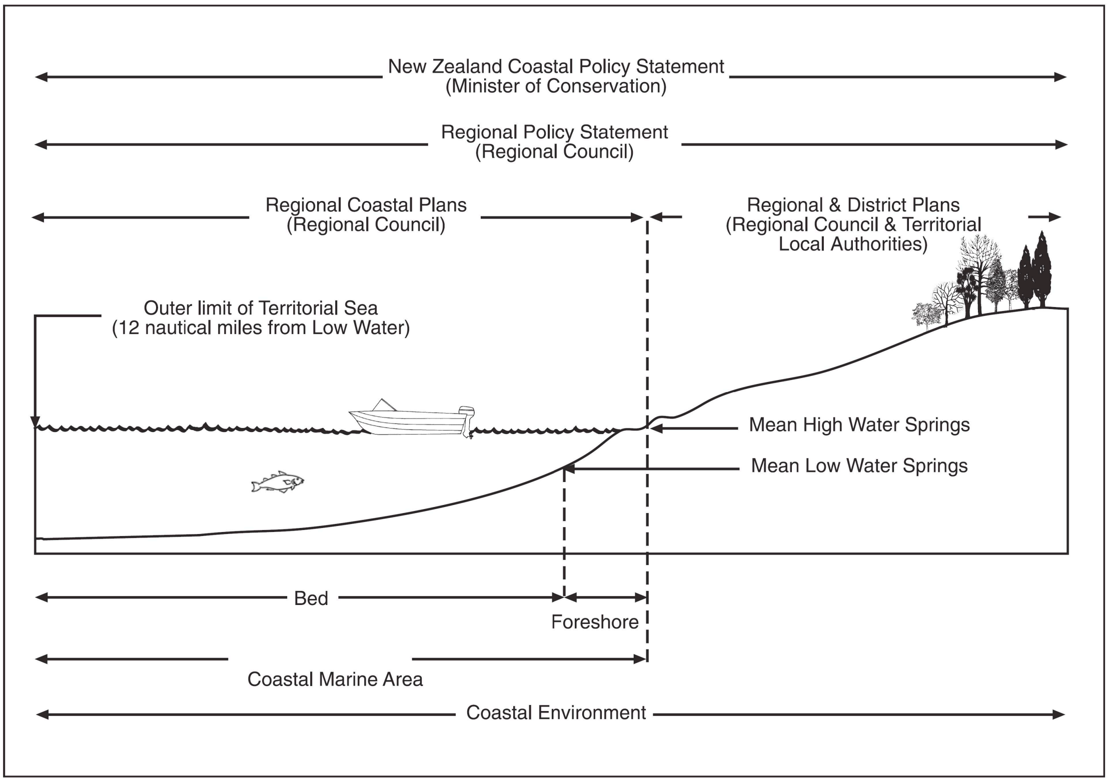


Figure 2.7: Management framework of the coastal environment in New Zealand (Environment Canterbury, 2005, p. 1-4).

2.3 Methodologies for studies involving coastal lagoons

Studies of hapua type coastal lagoons in New Zealand have focused on the geomorphology of these systems (Hart, 1999; Hart, 2007, 2009a, 2009b; Hart & Bryan, 2008; Kirk, 1983; Kirk & Lauder, 2000; McHaffie, 2010), and studies of coastal lagoons worldwide have typically focused on the ecological and physical aspects (Barnes, 1989; Bird, 1994; Comin *et al.,* 1991; Herrera, 1994; Jones *et al.,* 2003; Kjerfve, 1986; Kjerfve & Magill, 1989; Kjerfve *et al.,* 1996; Lucena *et al.,* 2002; Marcovecchio *et al.,* 2006; Nichols & Boon, 1994; Pereira *et al.,* 2009). The majority of coastal lagoon studies have not considered both the geomorphology and ecological aspects, and how they are related. As a result, this study was a combination of these two common approaches.

2.4 Methodologies used in this study

This study involved two types of investigation, short-term baseline studies, and long-term analysis of the hapua area and shoreline from aerial photographs using GIS. Long-term changes were analysed so that the 'natural' variation in the hapua morphology could be determined. It also aided in identifying and understanding the vulnerability of this environment to changes over longer time periods. Long-term flow and water quality data for the lower river was also analysed to aid in the analysis of the current conditions and the data collected in this study.

The major focus of this study was on the collection of baseline data. This information was needed due to the lack of knowledge about the current health of this vulnerable system, and how water properties respond to external influences such as storms and floods. The collection of baseline information allowed for the current health of the waterway to be evaluated, and to determine the major controls of hapua health. Baseline information is also vital in order for the impacts on the hapua to be determined if there is any change in the river hydrological regime, or any major changes in the river catchment in the future.

The collection of baseline data included information about sediment processes, water quality parameters (physical and chemical), and nutrients. These parameters were chosen due to the lack of information about these in this hapua, and since they are commonly used as indicators of waterway health in both rivers and coastal lagoons (Clapcott *et al.,* 2011; Ongley, 1996). These parameters were also chosen, as they are likely to be altered if there is a change in the hydrological regime or activities in the river catchment. A number of parameters were used since more than one is required to give a reliable representation of waterway health, and for effective management practices to be put in place (Marcovecchio *et al.,* 2006).

To collect baseline information, field and laboratory methods were used. Most of the methods used were standardised techniques, or based on methods used in other studies. For example, the standardised technique using sieves in the laboratory was used for investigating sediment composition. Because of the dynamic nature of the study site, in some cases more than one method was used to investigate the same parameter. This was to allow for the suitability of the different methods to be evaluated and the most appropriate method for this study site to be determined. For instance, both sediment traps and water samples were used to investigate suspended sediment.

While some techniques such as those used for measuring suspended sediment have advanced in recent years, some were not particularly useful due to the nature of the study site. Methods were therefore chosen carefully based on a range of factors such as expense, access to the study site, and logistical constraints. Water samples for suspended sediment and nutrient analysis were collected in the field, and then processed in the laboratory. Sediment from the lagoon bed was also collected and taken back to the laboratory for analysis. Some aspects of the fieldwork did not require processing in the laboratory. For instance, water parameters were measured and recorded in the field and then downloaded ready for statistical analysis. Deploying equipment such as time-lapse cameras and a water level recorder in the field gathered other baseline information.

2.4.1 Baseline information in different energy conditions

Baseline information was gathered in three main energy conditions. These included low energy, flood, and sea storm conditions. These were chosen as they were deemed the most common conditions and most influential in terms of hapua health and characteristics of the water. They were also chosen due to the major influence that both coastal and fluvial processes can have on hapua (Hart, 2007; Kirk, 1991).

Low energy conditions were deemed present when there was no overtopping of waves over the barrier, and when the river flow was below 60 m^3/s at the State Highway 1 (SH1) monitoring site on the Hurunui River. A number of low energy events were sampled. Samples for suspended sediment were taken on the 13th of May 2012 when the mean daily river flow was 37 m^3/s, and the 24th of September 2012 when the river flow was 59 m^3/s. Water samples for nutrient analysis were also taken during low energy conditions on the 24th of September 2012 and on the 13th of July 2012 when the mean daily flow at SH1 was 40.6 m^3/s.

A number of flood events were also sampled. Water samples for suspended sediment analysis were taken on the 25th of June 2012 just after the flood peak when the mean daily river flow was 147 m^3/s, and the second on the 9th of August 2012 when the mean daily river flow was 221 m^3/s. A flood with a mean daily river flow of 535 m^3/s was sampled for nutrients on the 2nd of August 2012.

Water samples for suspended sediment and nutrient analysis were taken during a storm on the 7th of November 2012 when waves were arriving at the Canterbury wave buoy from the south to south south-east and the significant wave height was around 2.75 m, and the river flow was 67 m^3/s.

2.3.2 Baseline information in different areas of the hapua

Baseline information was also gathered in different areas of the hapua and at different stages of the tide to see whether there were spatial differences and to see whether the backwater effect of the tide had an influence on the water quality parameters and water quality. Two low energy events and two floods were sampled for suspended sediment, water temperature, conductivity, dissolved oxygen, and pH. Samples were taken at high tide, mid tide, and low tide to see if the backwater effect of the tide had any influence on these parameters.

The number of sampling events was limited by the need for high tide occurring in the morning when it was daylight, and low tide in the afternoon before nightfall. The majority of the field period occurred over the winter months, hence the number of daylight hours was limited. Winter is also when the greatest river flows typically occur, limiting the number of low flow events. More flood events were not sampled due to the need for the flood occurring when high tide was in the daylight hours of the morning, and low tide in the evening before nightfall.

2.3.3 Sample site details

Five sample sites were initially chosen based on visual and physical differences such as water flow and proximity to the hapua outlet (Figures 2.8 and 2.9, and Table 2.2). This was to allow for each site to be representable of an area in the hapua that was unique with regard to physical characteristics. Site 1 was in the lower river and was chosen as it was not in the hapua and allowed for the conditions in the lower river to be investigated. Site 2 was at the start of the hapua and was chosen due to its proximity to the campground. Site 3 represented the main part of the hapua so was located halfway along the hapua. Site B was located along the backshore of the hapua in the ponded area, and site O was as close to the outlet as possible.

Fieldwork was conducted from May to November 2012. The collection of samples depended on specific conditions, so weeks to months lapsed between sampling events due to the need for these conditions to occur. Because of the nature of the dynamic environment, the study site morphology often changed significantly within a short period of time, especially at the outlet, as well as the position of the ponded area.

Unlike the other sites that did not change significantly in their position, sites B and O changed depending on the position of the outlet and the ponded backshore of the hapua. Therefore sites B and O had to be altered according to the conditions and morphology at the time of sampling. Site B represented the backshore area so was located along the backshore of the hapua at the northern end where the water was ponded. This site was moved between sampling events to where the water was the most ponded. Site O was located as close to the outlet as possible. This changed depending on the position of the outlet. Because the dynamic position of sites B and O, these sites were labelled according to the sampling event (Table 2.3). Each sampling event had an associated number with the site. For instance, for the suspended sediment and water parameter sampling event on the 13th of May, the backshore site was labelled B1, and the outlet site O1. All possible measures were taken to ensure that the sites were as similar as possible between sampling events.

Each time the study site was visited, observations were noted, especially the sea conditions and the position of the outlet. This was useful for helping to predict storm events, as well as to help to explain any unusual results.

Figure 2.8: Overall sample site framework at the Hurunui River hapua, with the five sample sites and the location of the time lapse cameras water level recorder (Land and Information New Zealand, 2012).

Table 2.2: Details of the characteristics of each of the sample sites.

Site	Characteristics
1	Riverine, shallow, fast flowing compared to the other sites, substrate composed of cobbles, shaded.
2	Shaded, relatively still water, soft substrate, with some areas composed of cobbles during the first low energy and flood events. During the second flood event this site was by the main river channel, had a swift flow, and had a cobbled substrate. During the storm event this site was in the same location as the first low energy and flood events, was shallow, ponded and had a cobbled substrate with some fine sediment.
3	End of the road, halfway along the hapua, soft substrate, shallow, unshaded.
B	Shaded, ponded water away from the main current, substrate composed of cobbles and small boulders.
O	At the outlet, swift current, substrate composed of sand and gravel, dynamic environment.

Figure 2.9: Photographs of the sample sites, site 1 (top left), site 3 (top right), site 2 (bottom left), and site B (bottom right). Site O is not included as it was significantly different each sampling event.

Table 2.3: Details of the site names for the backshore and outlet sites in each of the sampling events.

Date	Event	Samples	Site names	
13 May 2012	Low energy	Suspended sediment, water parameters	B1	O1
24 September 2012	Low energy	Suspended sediment, water parameters, nutrients	B2	O2
25 June 2012	Flood	Suspended sediment, water parameters	B3	O3
9 August 2012	Flood	Suspended sediment, water parameters	B4	O4
7 November 2012	Storm	Suspended sediment, water parameters, nutrients	B5	O5
13 July 2012	Low energy	Nutrients	B6	O6
2 August 2012	Flood	Nutrients	B7	O7

2.3.4 Safety considerations

During sea storms, waves often wash over the barrier, making it hazardous and unsafe to access (Figure 2.10). The barrier can also breach in periods of high wave energy and river flow making the outlet especially dangerous during storms and floods (Figure 2.11). Because of these safety concerns, sampling was limited to the landward side of the hapua, and the outlet was only sampled when it was deemed safe enough.

Figure 2.10: Waves washing over the barrier during a sea storm on the 7th of November 2012.

Figure 2.11: The mouth of the Hurunui River hapua during a flood on the 9th of August 2012.

2.9 Summary

This chapter has detailed the common approaches for studying coastal lagoons. The overall methodology approach used in this study was then discussed with details on aspects such as short-term baseline information, site details, and safety considerations. Baseline information was collected at different sites to investigate any spatial differences throughout the hapua. Baseline information was also collected at different stages of the tide and in different energy conditions.

The sampling program had to take into account a range of factors including: daylight hours, time of day when high and low tide occurred, safety considerations close to the outlet, and the dynamic nature of the geomorphology of the study site.

A range of parameters were measured to give an indication on the current health of this hapua, and how the water quality and sediment processes are affected by an external influences. This study also involved an analysis of the long-term geomorphology of this hapua so that the vulnerability of this system could be assessed.

The details of the methods used for each parameter and the results are presented in the following four chapters.

Chapter 3: River hydrology, water quality, and wave conditions

3.1 Introduction

This chapter focuses on the coastal and river boundary conditions of the Hurunui River hapua, that is, the conditions in the river and at sea that form the external processes and inputs that impinge upon the lagoon system. These conditions are assessed over monthly and yearly scales. An understanding of the long term trends in the river hydrology and water quality in the lower Hurunui River, and the wave conditions near the river mouth are fundamental for understanding, and giving context to the current conditions at the Hurunui River hapua. This chapter presents the results of the temporal trends in flow regime, nutrient concentrations, and other water quality parameters over both monthly and yearly time scales at the SH1 site on the Hurunui River over the past 7 years and 10 months for nutrient and water quality parameters, and 10 years and 11.5 months for river flow. It also presents the results of the significant wave height and direction at the Canterbury Wave Buoy over the last 12.5 years.

River flow and water quality data were obtained from Environment Canterbury for the State Highway 1 (SH1) monitoring site on the Hurunui River (Figure 3.1). This site is the closest Environment Canterbury monitoring site to the river mouth. Mean daily flow data from the 1st of January 2002 to the 19th of November 2012 were analysed to assess monthly and annual trends. Monthly water quality data collected from January 2005 to October 2012 were used to assess monthly and annual trends. This water quality data included: ammonia nitrogen, nitrate + nitrite nitrogen, total nitrogen, total phosphorus, dissolved reactive phosphorus, dissolved oxygen, pH, and water temperature.

Wave data from the Canterbury wave buoy were also obtained for the period 6th of February 1999 to the 1st of September 2012. This buoy is located 17 km east of Le Bons Bay at a depth of 76 m and wave data is recorded every 30 minutes (Environment Canterbury, 2012a). The data were analysed to assess the mean significant wave height and wave direction.

The data were analysed in *Microsoft Excel* using a variety of statistical methods. Time series analysis was used to examine seasonal and annual trends in flow, nutrient, and water quality parameter data. Trendlines were used to investigate annual trends, and the relationships between some parameters such as flow and dissolved oxygen concentration. Not all of the months in each year contained data for each parameter. In some months, nutrient concentrations were below the detection limit. For statistical analyses a below detection limit result half that of the detection limit was used. Wave data was analysed by the use of a wind rose.

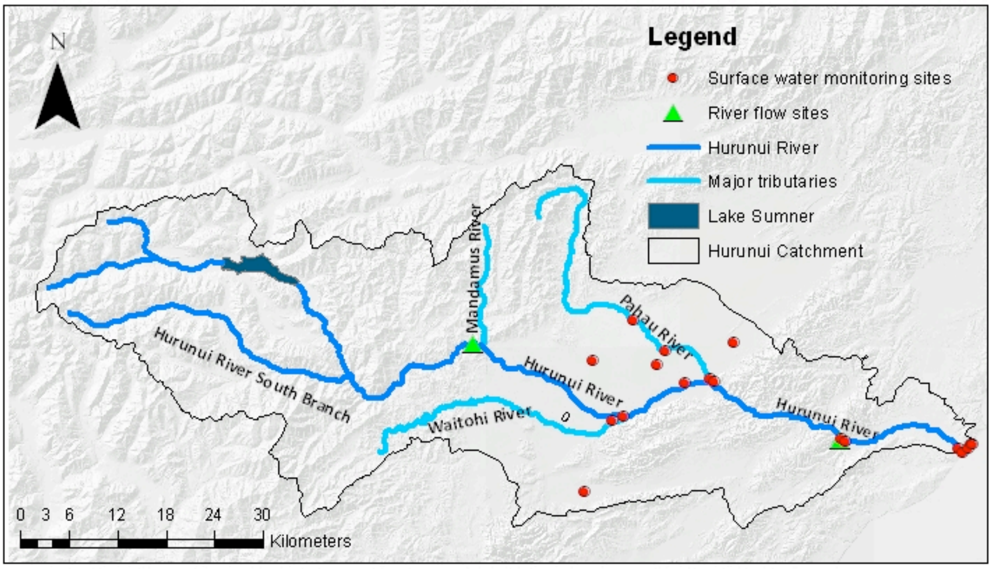


Figure 3.1: Location of the Hurunui River, tributaries, with the flow recorder sites and surface water quality sites sampled by Environment Canterbury.

This chapter is divided into five sections: wave climate is presented in section 3.2, flow regime in section 3.3, nutrients in section 3.4, and pH, water temperature and dissolved oxygen in section 3.5. Each section is divided into three subsections: a literature review, results, and an interpretation and discussion. This chapter concludes with an evaluation of limitations and errors in section 3.6, and a summary in section 3.7. This chapter addresses the following research objective:

- to investigate the past monthly and annual trends in hydrology, nutrient concentrations, and other water quality parameters in the lower Hurunui River, and to investigate the past trends in significant wave height and direction along the Canterbury Coast.

3.2 Wave climate

River mouths are influenced not only by fluvial processes, but also marine processes (Carter & Woodroffe, 1994; Hart, 1999; Hart, 2009b). The dominance of marine processes at river mouths vary from minimal influence, to a high degree of influence such as those along the east coast of the south island of New Zealand (Carter & Woodroffe, 1994). Aspects such as wave direction and magnitude must be taken into account in order to understand the processes occurring at river mouths, especially at those such as hapua, which are dominated by marine processes (Kirk, 1991).

The wave climate around New Zealand is variable, and this is due to the variation in swell, winds, and influence of the Southern Oscillation Index. Southern New Zealand regularly experiences low pressure trough systems from the Southern Ocean with north-west and south-west fetches (Laing, 2000). The east coast of New Zealand typically has smaller waves compared to the west coast (Figures 3.2 and 3.3) (Laing, 2001; Pickrill & Mitchell, 1979). Significant wave height varies seasonally, with higher values in the winter compared to the summer, although the difference throughout the year is minimal (Figure 3.4) (Gorman *et al.,* 2003; Laing, 2000; Pickrill & Mitchell, 1979). Prevailing waves from the south or southeast are typical of the Canterbury Bight (Pickrill & Mitchell, 1979), and waves can rapidly increase in size in the presence of fronts moving up the west coast (Laing, 2001).

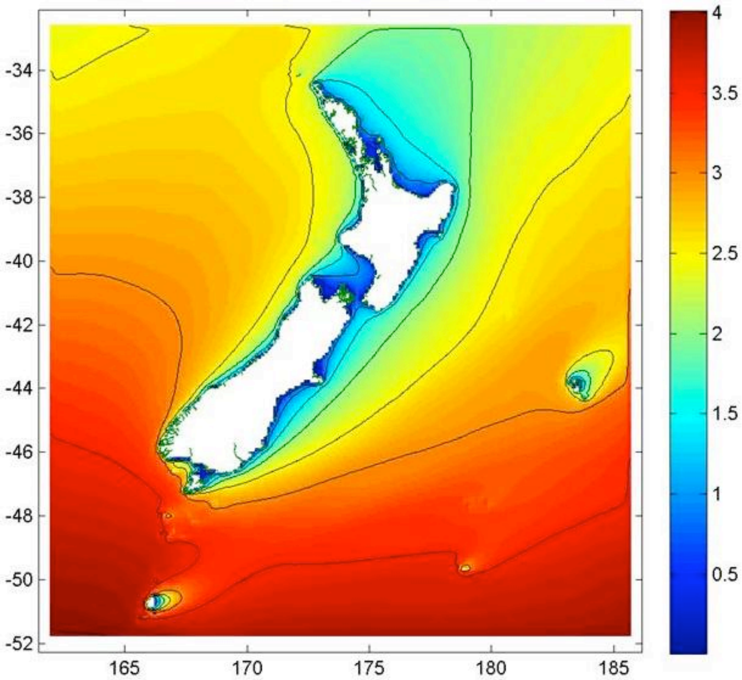


Figure 3.2: Spatial differences in the significant wave height around New Zealand from a 45-year model hindcast, with latitude and longitude (NIWA, 2012c).

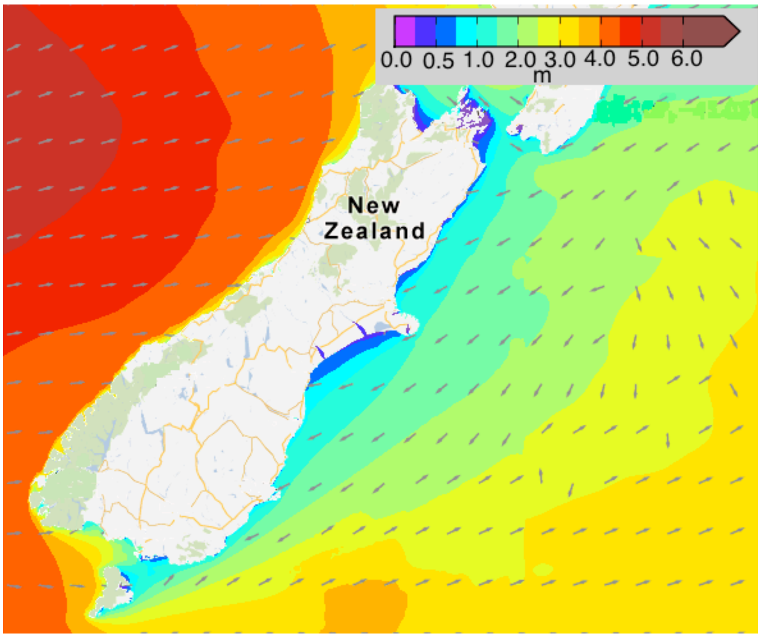


Figure 3.3: Variation in the significant wave height and direction around the south island of New Zealand on the 1st of October 2012 (MetOcean Solutions Limited, 2013).

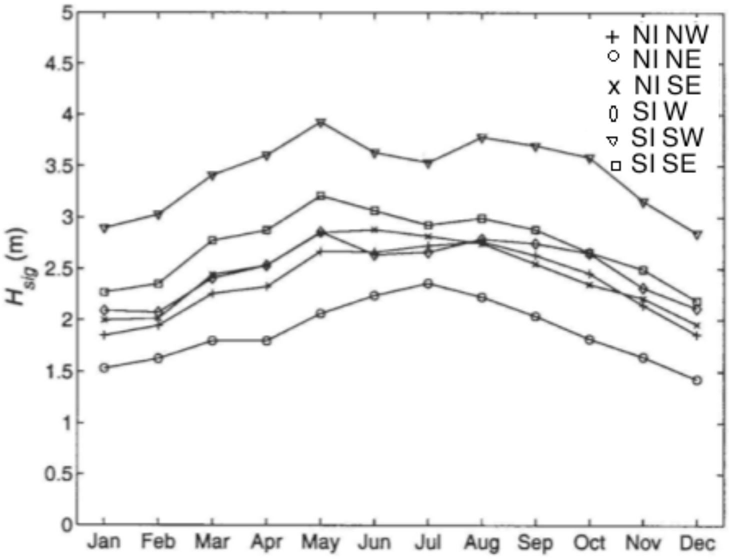


Figure 3.4: Monthly means of significant wave height at different locations around New Zealand (NI NW = North Island north west, NI NE = North Island north east, NI SE = North Island south east, SI W = South Island west, SI SW = South Island south west, SI SE = South Island south east (Gorman *et al.,* 2003, p.601).

The local wave climate is measured by the Canterbury Wave Buoy anchored off the coast of Banks Peninsula. Although it is some 100 km south of the Hurunui River mouth, the data are still relevant to the wave climate at the river mouth (Figure 3.5). Data from this wave buoy are used to simulate the wave height and direction along the Canterbury coastline every 3 hours (NIWA, 2013). The model takes into account the effect of local winds in Christchurch, and refracts the deep water waves to the coast using a wave refraction model (NIWA, 2013). Deep water waves are waves that have a depth that is greater than half of the wave length (Garrison, 2011). The resulting image represents the deep-water wave conditions along the Canterbury coast (NIWA, 2013).

The NIWA wave refraction model shows that the significant wave height and wave direction at the Hurunui River mouth is similar to the conditions at the wave buoy. However, it is possible that the wave direction at the Hurunui River mouth is slightly different to the wave direction at the wave buoy. For instance, on the 16th of January 2013, the waves at the buoy were from the south-east, whereas the waves at the Hurunui River mouth were from the east south-east (Figure 3.5). Alternatively, MetOcean Solutions Limited uses oceanographic and atmospheric forecast models to predict wave height and direction (Figure 3.6) (MetOcean Solutions Limited, 2013). Although the results from the wave buoy data and the model produce similar predictions for wave height, there appears to be some discrepancy in wave direction. On the 16th of January 2013 the wave buoy result indicated waves arriving at the Hurunui River mouth were from the east south-east, whereas the MetOcean Solutions Ltd model estimated the waves were from a more southerly direction. Because of the availability of data from the wave buoy, these data are used to give an indication of the wave climate at the Hurunui River mouth.

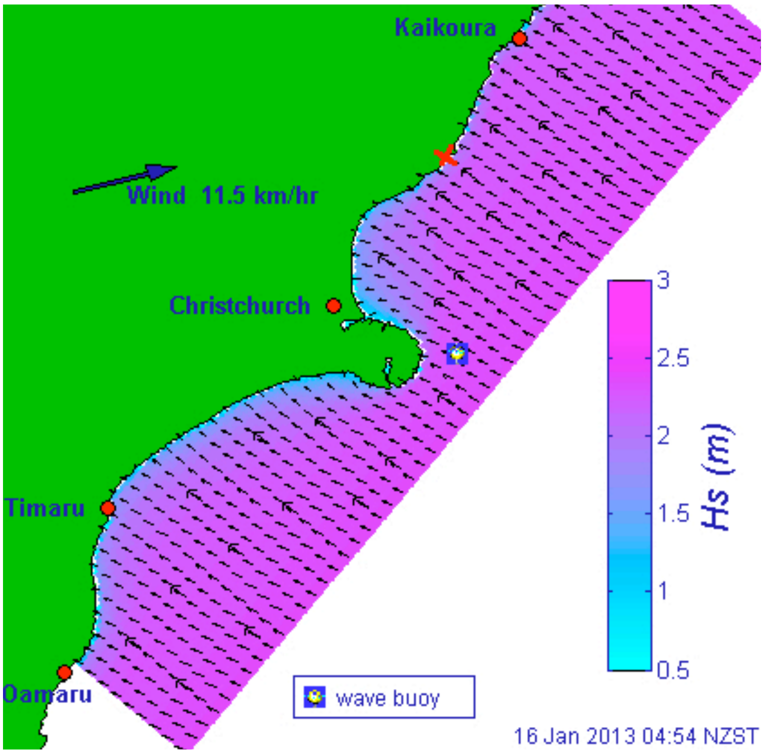


Figure 3.5: Significant wave height and direction along the Canterbury coastline on the 16th of January 2013, with the approximate location of the Hurunui River mouth marked by an x (additonal wave direction arrows have been added for clarity) (NIWA, 2013).

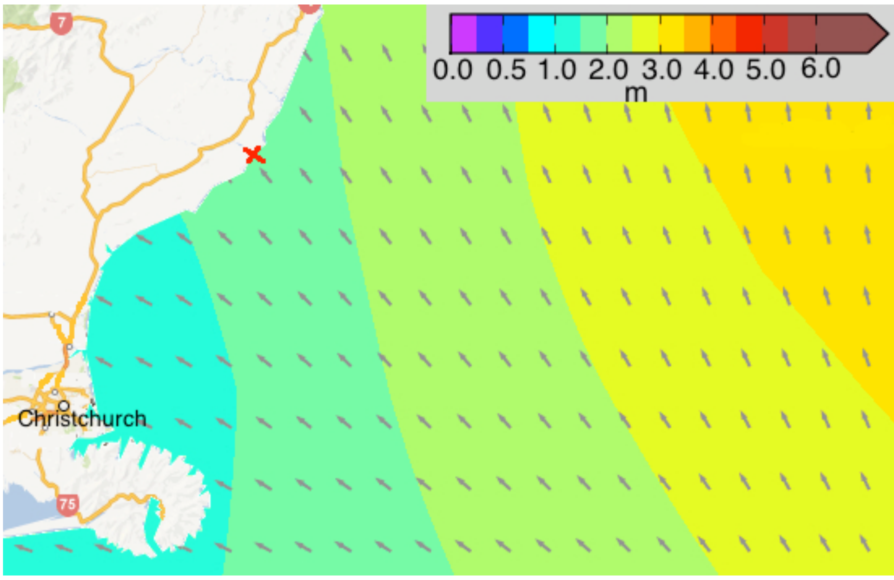


Figure 3.6: Wave height and direction (indicated by the arrows) along the Canterbury coastline on the 16th of January 2013, with the location of the Hurunui River mouth marked by an x (MetOcean Solutions Limited, 2013).

Data from the Canterbury Wave Buoy is sent via radio signal to a computer at NIWA (Environment Canterbury, 2012a). Data includes the direction that the waves arriving at the buoy are from, wave height, and wave timing. Wave height is recorded as significant wave height. This is the average height of the largest 33% of waves over a 20 minute period. This is recorded since the larger waves are the most important for hazards. Wave timing is how far apart the waves arriving at the buoy are and is measured in seconds. The greatest periods will be from waves that have a long travel distance (Environment Canterbury, 2012a).

3.2.1 Wave climate results

From the 6th of February 1999 to the 1st of September 2012, 39% of the waves arriving at the wave buoy were from the south, with 27% of waves from the southwest, 19% from the east, and 13% from the southeast (Figure 3.7). Twenty-six percent of the waves had a significant wave height of 1.5-2.0 m, although most of the waves from the southeast had a significant wave height of 4.0-4.5 m. Waves arriving from the south were the most variable in significant wave height. These waves ranged from 0.5-5.0 m, waves 1.5-2.0 m occurred the most frequently (11.7%), while some wave heights (0.5-1.0, 4.0-4.5, and 4.5-5.0) occurred less than 1% of the time.

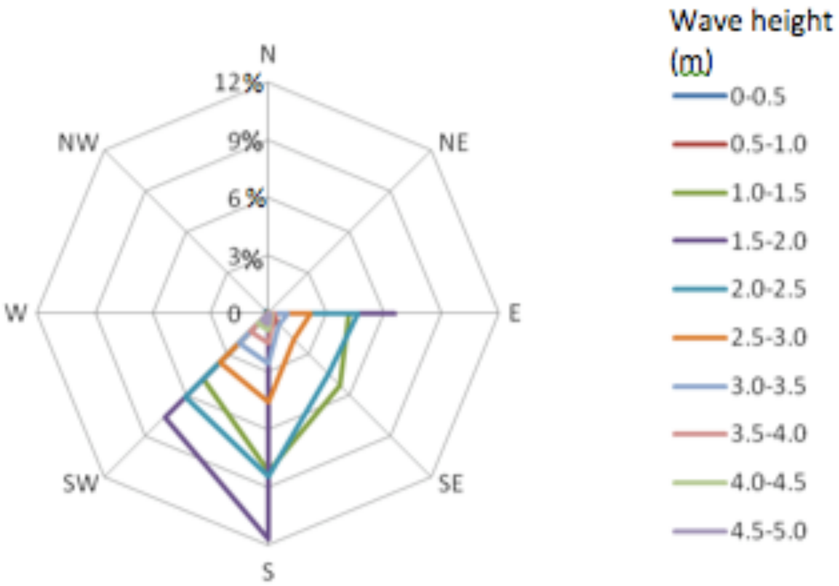


Figure 3.7: Percentage frequency significant wave height and direction of wave approach recorded at the Canterbury wave buoy from the 6th of February 1999 to the 1st of September 2012 (data sourced from Environment Canterbury).

3.2.2 Wave climate interpretation and discussion

Over the past 12.5 years, most of the waves at the wave buoy off Banks Peninsula have come from the south and southwest. Although the Hurunui River mouth is north of the wave buoy, it is likely that the dominant wave direction has been similar. Because of the refraction of the waves around Banks Peninsula, it is possible that the waves reaching the coastline adjacent to the Hurunui River mouth have been more easterly compared than the waves reaching the wave buoy. Waves arriving at the buoy are generated by depressions to the south of New Zealand, so are larger in size compared to smaller northerly waves that are generated by local conditions (Macky *et al.,* 2000). Because most of the waves at the buoy have been from the south, it is concluded that waves at the buoy, and hence the Hurunui River mouth, are generated by depressions to the south of New Zealand.

The dominant wave direction over the past 12.5 years has been typical of the Canterbury Bight historically (Pickrill & Mitchell, 1979). It is likely that there are slightly more waves that arrive from the south during the winter than the summer at the coastline adjacent to the Hurunui River mouth (Pickrill & Mitchell, 1979).

New Zealand is dominated by swell from the west and southwest, hence the east coast experiences smaller waves than the west coast (Gorman *et al.,* 2003; Laing, 2000; Pickrill & Mitchell, 1979). This is evident in the data collected over the past 12.5 years from the Canterbury wave buoy when compared to the wave climate of the west coast of the South Island. On the west coast of New Zealand, the prevailing wave height is 1.0-3.0 m, while the prevailing wave height over the past 12.5 years along the Canterbury coast has been 1.5-2.0 m; this is consistent with the expected smaller waves typical of the east coast. Like the wave direction, weak seasonal trends in wave height are likely, with waves slightly greater in magnitude during the winter compared to the summer (Laing, 2000; Pickrill & Mitchell, 1979).

3.3 Flow regime

The hydrology of a river plays a crucial role in its amenity, recreational, and ecological values (Mosley, 2002). Over time, while it may appear that there has been a minimal amount of change in the flow regime in the short term, there may in fact be different trends over longer time scales. For instance, there may not appear to be a change from month to month, but there may be a change when comparing between years. Knowledge of the pre-existing flow regime is important for understanding the current regime and its impact on the health of the waterway. This knowledge can assist in predicting how the riverine ecology and morphology will be impacted if there is an alteration in the flow regime (Mosley, 2002). The following results are based on data collected from the 1st of January 2002 to the 19th of November 2012 at the SH1 site on the Hurunui River. This is equal to 10 years and 11.5 months.

3.3.1 Flow regime results

The highest mean monthly flow at the SH1 site on the Hurunui River was during spring, with October having the highest mean flow of 106 m^3/s (Figure 3.8). The mean monthly flow ranged between 36.3 m^3/s (March), to 106 m^3/s (October). The lowest flow occurred over the summer and autumn from December to April. January typically had a mean flow of 54.7 m^3/s, but a maximum flow of 145.8 m^3/s did occur. March had the smallest amount of variation in mean flow, and August had the greatest.

There appears to have been no trend of an increase or decrease in the mean annual flow over the last 10 years and 11.5 months (R^2=0.04) (Figure 3.9). The mean and maximum annual flow varies from year to year, with the greatest variation in the maximum annual flows. The minimum flow remained consistently below 50 m^3/s, but the maximum flows were more variable. 2005 had the lowest annual maximum flow of 66 m^3/s, while 2007 had the highest annual maximum flow of 208.3 m^3/s over the past 10 years and 11.5 months.

Mosley (2002) uses a flood threshold of the median flow multiplied by 3. Based on this approach, the flood threshold was 143.7 m^3/s. The number of days when the mean flow exceeded 143.7 m^3/s ranged from 0 in 2005 to 37 in 2010 (Figure 3.10). The average number of days per year in the past 10 years and 11.5 months that exceeded this flow has been 22 days. The lower quartile value of 32.5 m^3/s was used as the level for low flow. In the past 10.5 years, the number of days that had a mean flow under 32.5 m^3/s ranged from 40 in 2011, to 165 in 2007. The average number of days per year in the past 10 years and 11.5 months that had a mean daily flow under 32.5 m^3/s has been 86.6 days.

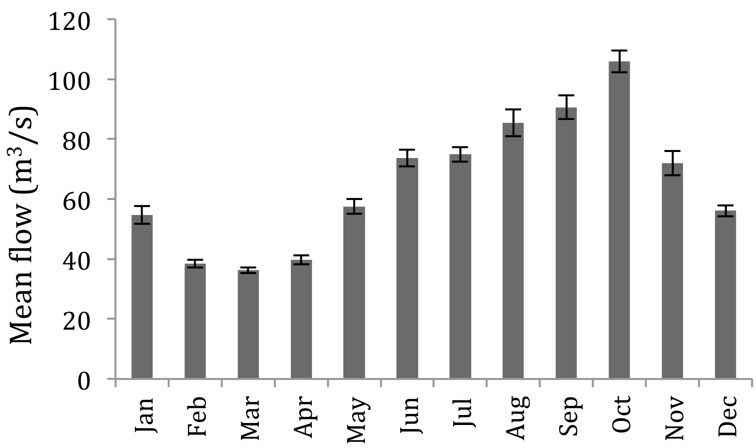


Figure 3.8: Mean monthly flow with error bars for the past 10 years and 11.5 months at the SH1 site on the Hurunui River (data sourced from Environment Canterbury).

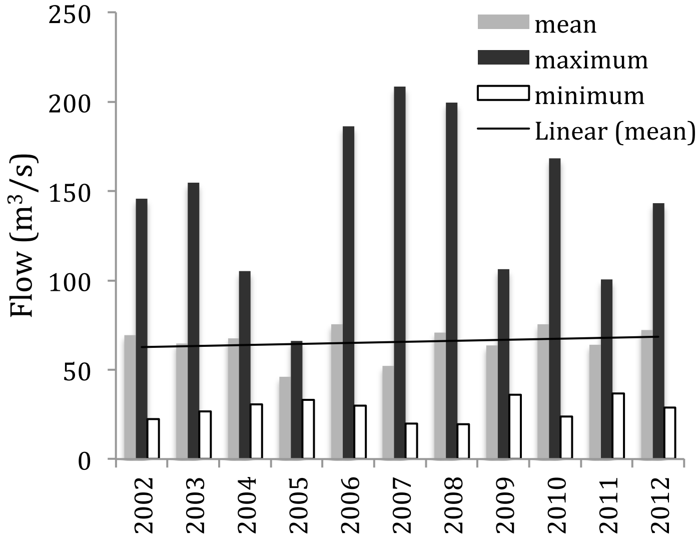


Figure 3.9: Minimum, mean, and maximum annual flow for the past 10 years and 11.5 months at the SH1 site on the Hurunui River (data sourced from Environment Canterbury). The 2012 data was not for a full year.

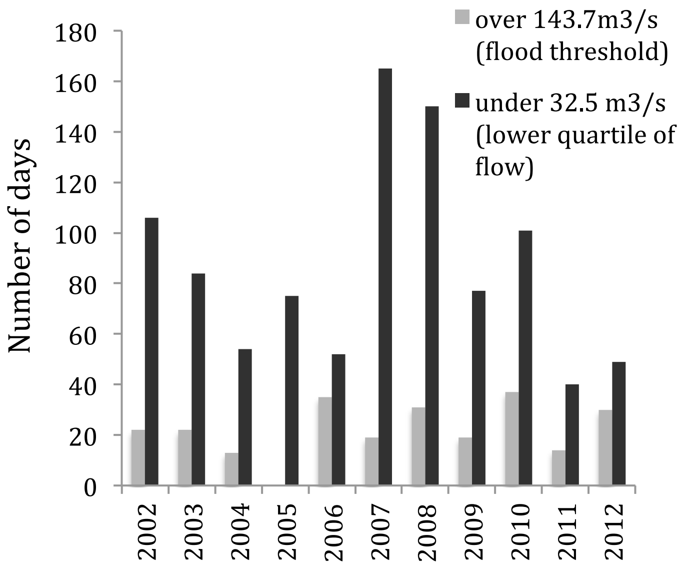


Figure 3.10: Number of days over the past 10 years and 11.5 months with a mean daily flow over 143.7 m^3/s, and a mean daily flow under the lower quartile of 32.5 m^3/s (data sourced from Environment Canterbury).

3.3.2 Flow regime interpretation and discussion

Analysis of the river flow of the Hurunui River at SH1 over the past 10 years and 11.5 months shows that there have been seasonal trends. The lowest flow was during summer and autumn, although higher flows above the flood threshold were not uncommon in January. Because Lake Sumner moderates flows, snowmelt is not a major contributor to the flow in the Hurunui, although it does have a small influence when snowmelt is at its greatest in late winter and spring (Mosley, 2002).

There is much variation in the seasonal trends in the flow regime of lake-fed rivers in New Zealand, yet the flow regime of the Hurunui River where the lowest flow occurs during the summer due to high evapo-transpiration, and the greatest floods occur during the spring, is typical of Canterbury rivers that originate near the Main Divide of the Southern Alps (Environment Canterbury, 2008; Hayward *et al.,* 2003; Mosley & Environment Canterbury, 2004). Some rivers such as the Rakaia have a slightly different seasonal trend in flow regime as the lowest flows occur during winter when precipitation is locked up as snow (Kirk, 1991; Smakhtin, 2001). Typical of Canterbury rivers, the highest flow in the Hurunui River usually occurs during the spring when snowmelt is at its highest (Mosley, 2002). However, the presence of floods in the summer is not unusual for rivers including the Hurunui River in the Canterbury Region that originate near the Main Divide where rainfall is high year round. Despite water being abstracted for irrigation both on the Hurunui River and the Waiau River, the flow regimes remains characteristic of alpine fed rivers in Canterbury (Mosley, 2002).

The variation in the water flow throughout the year is typically due to a combination of natural and anthropogenic factors. Natural factors can include snowmelt, rainfall, and groundwater inputs (Smakhtin, 2001). Anthropogenic factors can include: afforestation, soil drainage, groundwater abstraction, and surface water abstraction (Smakhtin, 2001). Unlike other rivers that have had their seasonal river flow altered by water abstraction (Maheshwari *et al.,* 2006; Wang *et al.,* 2006), the flow regime of the Hurunui River has remained largely unaltered despite anthropogenic surface water abstraction (Mosley, 2002). The lowest mean monthly flows over the past 10 years and 11.5 months have not been altered from the 1957 to 2000 period despite water abstraction for irrigation. In both time periods, the lowest mean monthly flows occurred in February and March. Alternatively, there has been a shift in the trend for the highest flows. The highest mean monthly flows occurred in October in both time periods. However, from 1957 to 2000, the highest mean monthly flows occurred from September to November (Mosley, 2002), but over the past 10 years and 11.5 months the highest mean monthly flows have reached a maximum in October, followed by a decrease in November. It is likely that this recent change in the seasonal trend is due to a change in irrigation in the Hurunui River catchment.

The flood and seasonal regime of the Hurunui River has also remained largely unaffected by surface water abstraction, and this is due to the natural high variability in the natural flow regime (Mosley, 2002). Flood frequency and magnitude of the Waiau River also has most likely remained unaltered from 1974 to 2002 by large volumes of surface water abstraction (Mosley & Environment Canterbury, 2004). Despite the flood and seasonal trends being relatively unaffected in both of these rivers in earlier time periods, mean monthly flows in the Hurunui River, and baseflows in the Waiau River have decreased with surface water abstraction increases, especially in the irrigation season (Mosley, 2002; Mosley & Environment Canterbury, 2004). It is unknown whether there has been a change in the baseflows in the Hurunui River over the past 10 years and 11.5 months, as comparisons cannot be made with flow data further up the river since river flow increases with distance downstream (Mosley & Environment Canterbury, 2004). Flow data from the past 10 years and 11.5 months also cannot be compared with earlier data from the SH1 site on the Hurunui River since this was outside the aims of this study.

Although the seasonal trends in the hydrological regime of the Hurunui River have been largely unaltered by abstraction of water the last 10 years and 11.5 months, it is possible that the seasonal trends could be altered in the future. This could be in response to the expected change climate and snow cover in the Southern Alps of New Zealand (Mullan *et al.,* 2008). Snow cover is expected to reduce, and spring melt is expected to occur earlier in the year (Mullan *et al.,* 2008).

While distinct seasonal trends for the Hurunui River are evident over the past 10 years and 11.5 months at the SH1 gauge site, there has been no change in the average yearly flow from 2002 to 2012. This is despite the increase in surface water runoff from groundwater abstraction for irrigation in the Culverden Basin which has increased the flows in the tributaries, especially during the summer months (Ausseil, 2010). Mean annual flow and maximum yearly flow varied from year to year between 2002 and 2012, especially the maximum yearly flow. This demonstrates that the flood magnitude was highly variable during this time period. This fluctuation in the mean flow and the maximum flood peak between the years is typical of the Hurunui River (Mosley, 2002). This variability is also characteristic of rivers in the Canterbury Region that originate near the mountains as this trend is also evident for the Waiau, Waipara, and Ashburton Rivers (Mosley, 2002; Mosley, 2001, 2003). The variation from year to year is often related to variations in rainfall since precipitation throughout New Zealand can vary each year by up to 20% from the long term average (Mullan *et al.,* 2008).

It is likely that the temporal trends in the flow regime of the Hurunui River are influenced by the Interdecadal Pacific Oscillation (IPO), El Niño Southern Oscillation (ENSO), and global warming (Figure 3.11) (McKerchar & Henderson, 2003; Mosley, 2002). The effect of ENSO and the IPO on the rainfall and climate is highly variable across New Zealand. In Canterbury, air temperatures tend to be higher with more rainfall and less evapotranspiration during La Niña events (Mohssen *et al.,* 2011; Wratt *et al.,* 2012). In 2012, a La Niña event in New Zealand ended in April, and near normal conditions occurred for the remainder of the year (NIWA, 2012b). In El Niño years, eastern areas of New Zealand tend to have less rainfall and greater evapotranspiration. Regardless of the difficulties in determining the relative influence of ENSO on rivers in New Zealand, up to 25% of the year to year variation in temperature and rainfall in New Zealand may be attributed to ENSO (Wratt *et al.,* 2012). Despite this, of all the influences that ENSO has on the climate, the change in rainfall is considered to have the greatest impact on the hydrological regime of rivers (Mohssen *et al.,* 2011).

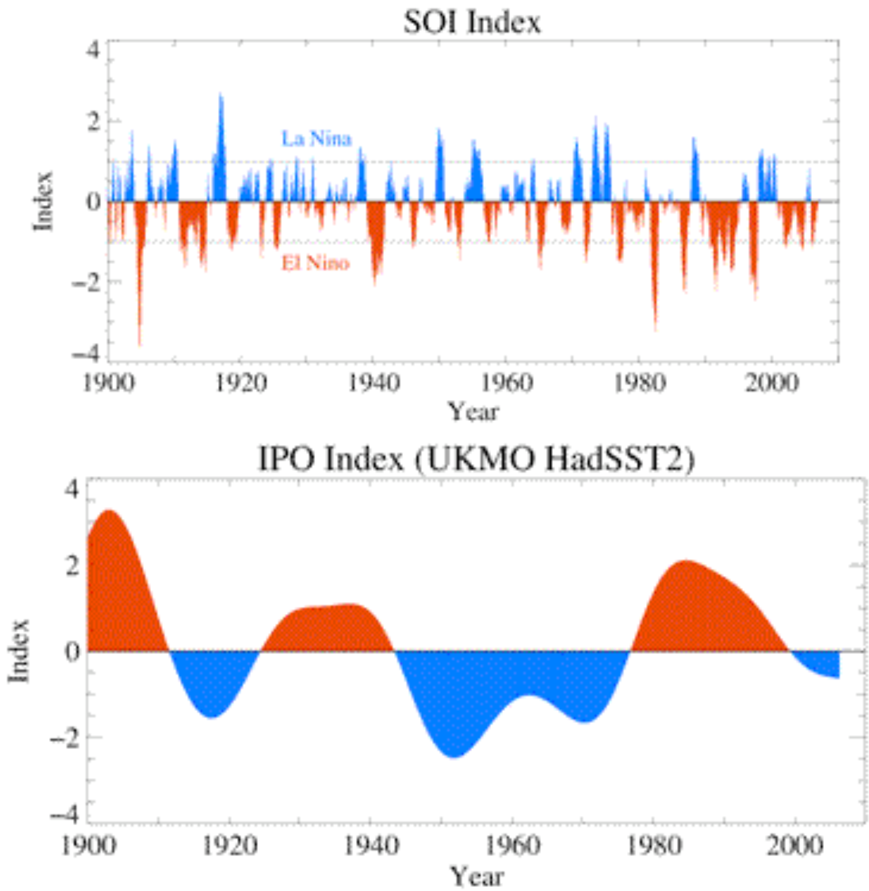


Figure 3.11: Southern Oscillation Index (SOI) and the Interdecadal Pacific Oscillation (IPO) from 1900 to 2006, La Niña is shown in blue and El Niño is shown in red (Mullan *et al.,* 2008, p.41).

While it has been identified that ENSO and the IPO have an influence on the hydrological regime of rivers in New Zealand, the degree of influence is difficult to decipher. Although these have been linked to the flow regime of some rivers such as the Yellow River in China (Wang *et al.,* 2006), and some rivers in Florida (Schmidt *et al.,* 2001), it is difficult to determine how much these have influenced the flow regime of the Hurunui River over the past 10 years and 11.5 months (McKerchar & Henderson, 2003; Mosley, 2002). The short time frame of the data of this analysis prevents any influence of ENSO and IPO on the hydrological regime to be determined. Where links have been made between these climatic factors and changes in flow regimes, much longer time frames have been analysed (Schmidt *et al.,* 2001; Wang *et al.,* 2006). At least 30 years of stream flow records is considered necessary to determine the influence of ENSO (Mosley, 2000), especially since these natural oscillations persist for seasons to decades (Mullan *et al.,* 2008). It is possible that the flow of the Hurunui River over the past 10 years and 11.5 months has been higher than normal since it is thought that New Zealand has recently been, and is currently still in a La Niña phase which brings more rainfall to the Southern Alps. While it is likely that these climatic factors have had an influence on the Hurunui River over the past 10 years and 11.5 months (Mosley, 2002), it is evident that much longer time frames must be studied to determine the amount and type of influence that these have had (Mosley, 2003).

Future predictions of the hydrological regime of the Hurunui River are difficult to determine because of a range of natural and anthropogenic influences. Firstly, it is uncertain how ENSO will alter precipitation in the Southern Alps in the future (Mullan *et al.,* 2008). It is possible that the flow of the Hurunui River will decrease in response to the expected increase in air temperatures and the decrease in rainfall on the Canterbury Plains, although the degree of change in precipitation will depend on whether it is a La Niña or El Niño year (Mullan *et al.,* 2008). Alternatively, the flow could increase due to the predicted increase in rainfall in the Southern Alps in response to the continued change in climate. Secondly, river flows can be indirectly influenced if other natural events occur such as volcanic eruptions that can alter the climate (Mullan *et al.,* 2008). Land use and water abstraction can also influence the hydrological regime of rivers. Water abstraction in this river has reduced the baseflow, especially during the irrigation season, rather than altering the shape of the annual flow regime (Mosley, 2002). Because of these interacting natural and anthropogenic influences, long-term trends in the hydrological regime of the Hurunui River over time is difficult to predict. Under future predictions about the change in climate, it is likely that the flow of the Hurunui River will reduce, which will have consequences for water quality (Larned *et al.,* 2004; Mullan *et al.,* 2008). Despite the unknowns, it is likely that the flow regime of the Hurunui River will continue to change in response to these climatic and anthropogenic factors.

While it is often difficult to determine the degree of influence that inter-decadal and inter-annual variations would have on the river flow regime, it has been shown that these can impact the coast. Inter-annual and inter-decadal variations in the rainfall and flood regime of a river can directly influence the opening regime of estuaries such as the San Dieguito Lagoon in California, and Tross Lake in south-eastern Australia (Rustomji, 2007). While there have been no specific studies addressing the relationship between the inter-decadal and inter-annual variation in flow regime on the shape and location of the Hurunui River mouth, it is likely that there is some degree of influence at this river mouth.

It is important to identify and understand the flow regime of rivers, not only to understand processes in the catchment, but for also understanding the impacts at the coast. The flow regime of a river has a direct influence on the river mouth and coast (Rustomji, 2007). The flow regime can have a direct influence on the shape of coastal forms such as estuaries and their connection to the sea (Rustomji, 2007). Fluvial processes are also important to hapua, especially for the transport of sediment during floods as it is a source of beach material along the adjacent coast (Hart, 2009a). Although the hydrological regime of a river can have significant impacts on the river itself, it is evident that the influence of this regime on the coastal environment must not be ignored.

3.4 Nutrients

To assess the current state, or the impact of any changes in the flow regime on waterway health, nutrient concentrations as well as the physical and chemical characteristics of the water are often measured. Nutrient concentrations give an indication of the waterway health both spatially and temporally (Ausseil, 2010). Nutrient enrichment is of concern due to its impact on biota (Environment Canterbury, 2009). For instance, if nitrogen and phosphorus levels are high, there is typically an over-stimulation of periphyton growth (Ausseil, 2010; Mosley, 2002). As a result, the water can become oxygen depleted and other biota such as fish can be harmed (Environment Canterbury, 2009). Nutrients that are tested for can include: dissolved reactive phosphorus, soluble inorganic nitrogen, ammonia nitrogen, nitrate and nitrite nitrogen, total organic nitrogen, total nitrogen, and total phosphorus (Hayward *et al.,* 2003). Because nutrients are found in different forms, a variety of forms are tested for (Environment Canterbury, 2009).

Variation in the nutrient concentrations in waterways can be driven by a range of factors including: surface runoff, especially in terms of phosphorus; subsurface or groundwater flows; irrigation for agriculture; algal growth; and the breakdown of organic matter (Ausseil, 2010; Environment Canterbury, 2009; Hayward, 2001; Hayward *et al.,* 2003). Some nutrients are affected by the chemical and physical characteristics of the water, for instance, the higher the pH and temperature of the water, the greater the toxicity of ammonia nitrogen especially for some fish species (Environment Canterbury, 2009; Hayward *et al.,* 2003). Nutrient concentration in a river is also influenced by the quality of water that flows into it from the tributaries, which is currently the case for the Hurunui River (Ausseil, 2010). Nutrient levels also depend on the flow regime of the river (Ausseil, 2010; Bintz *et al.,* 2003; Mosley, 2002).

3.4.1 Nutrients results

The records for nutrients were variable; nutrients were not recorded for every month in each year (Appendix 2). Some months and years had a more consistent record than other months and years. The following results are based on data collected from January 2005 to October 2012 at the SH1 site on the Hurunui River. This is equal to 7 years and 10 months.

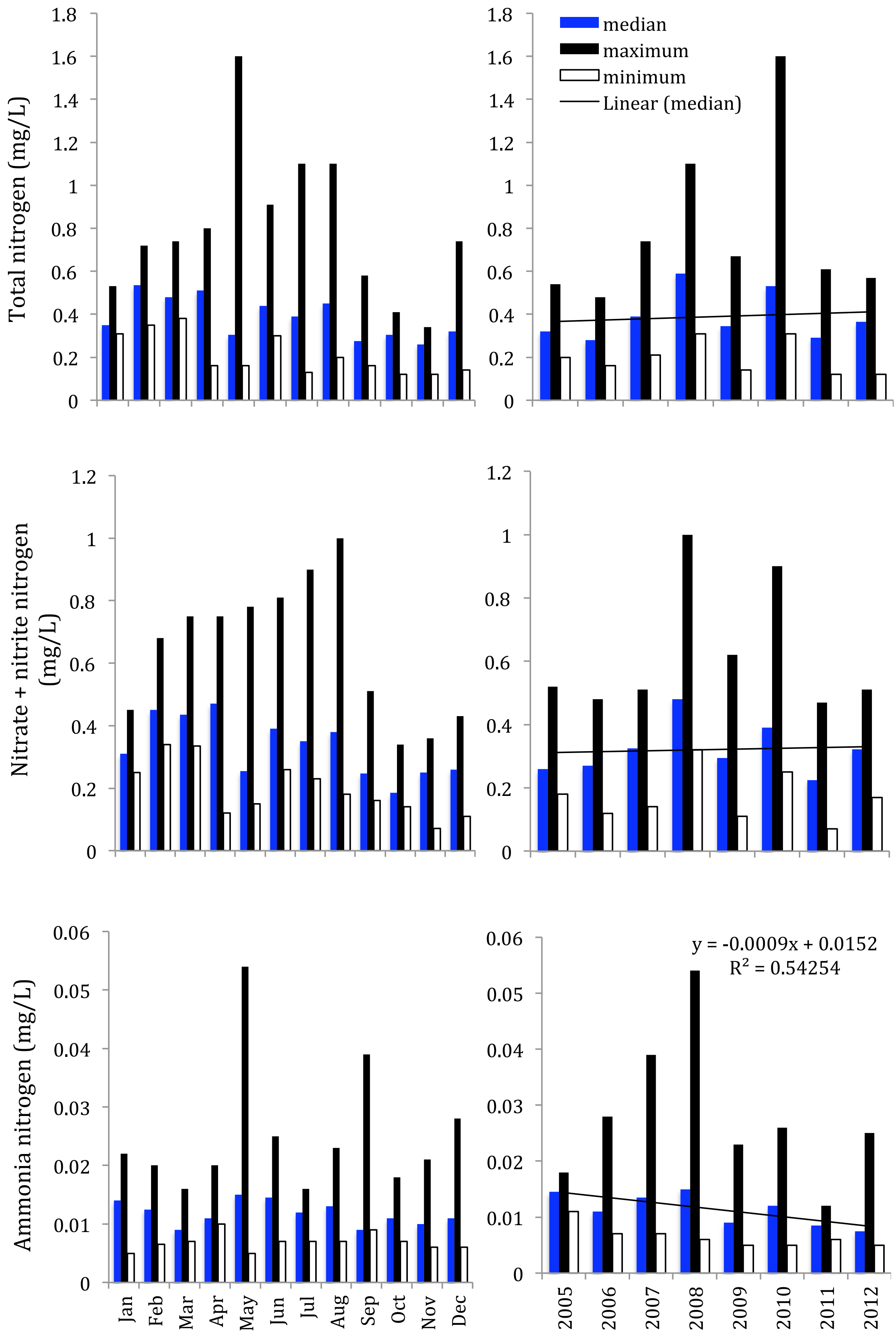
Based on data from 2005 to 2012 at the SH1 site on the Hurunui River, the highest monthly median total nitrogen concentration occurred in February (Figure 3.12). Monthly median total nitrogen concentration ranged from 0.26 mg/L in November to 0.54 mg/L in February. The highest monthly median concentration occurred during late summer and early autumn. The highest monthly maximum total nitrogen occurred in May, and the lowest monthly maximum values occurred in November. The median annual total nitrogen concentration ranged from 0.28 mg/L in 2006 to 0.64 mg/L in 2010. The highest maximum values occurred in 2010. There has been no change in the median annual concentration of total nitrogen from 2005 to 2012.

The highest nitrate + nitrite nitrogen monthly median concentration from 2005 to 2012 occurred in April (Figure 3.12). Monthly median nitrate + nitrite nitrogen concentration ranged from 0.19 mg/L in October, to a maximum monthly median concentration of 0.47 mg/L in April. The highest monthly median concentration occurred in late summer and early autumn. The highest monthly maximum concentration occurred in August, and the lowest in October. The median annual nitrate + nitrite nitrogen concentration ranged from 0.23 mg/L in 2011 to 0.48 mg/L in 2008. The highest maximum values occurred in 2008. There has been no change in the median annual concentration of nitrate + nitrite nitrogen in the past 7 years and 10 months.

From 2005 to 2012, the highest ammonia nitrogen monthly median concentration occurred May and June (Figure 3.12). Monthly median ammonia nitrogen concentration ranged from 0.009 mg/L in March and September to 0.015 mg/L. The highest monthly median concentration occurred in late autumn. The highest monthly maximum occurred in May, and the lowest in March. The median annual ammonia nitrogen concentration ranged from 0.006 mg/L in 2012 to 0.015 mg/L in 2005 and 2008. The highest maximum values occurred in 2008. There was a decrease in the median annual concentration of ammonia nitrogen from 2005 to 2012.

The highest total phosphorus monthly median concentration occurred in May and July (Figure 3.12). Monthly median total phosphorus concentration ranged from 0.008 mg/L in March to 0.06 mg/L in May and July. The highest monthly maximum concentration occurred in May, and the lowest in March. The median annual total phosphorus concentration ranged from 0.009 mg/L in 2005 to 0.04 mg/L in 2012. The highest maximum concentration occurred in 2010. There has been no change in the median annual concentration of total phosphorus from 2005 to 2012.

From 2005 to 2012, the highest dissolved reactive phosphorus monthly median concentration occurred in May and July (Figure 3.12). Monthly median dissolved reactive phosphorus concentration ranged from 0.002 mg/L in November to 0.0058 mg/L in July. The highest monthly maximum concentration occurred in May, and the lowest in January. The median annual total phosphorus concentration ranged from 0.002 mg/L in 2005 to 0.005 mg/L in 2006 and 2008. The highest maximum values occurred in 2010. There was no change in the median annual concentration of dissolved reactive phosphorus from 2005 to 2012.


Total nitrogen (mg/L)
median
maximum
minimum
Linear (median)
Nitrate + nitrite nitrogen (mg/L)
Ammonia nitrogen (mg/L)
y = -0.0009x + 0.0152
R^2 = 0.54254
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
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Nov
Dec
2005
2006
2007
2008
2009
2010
2011
2012

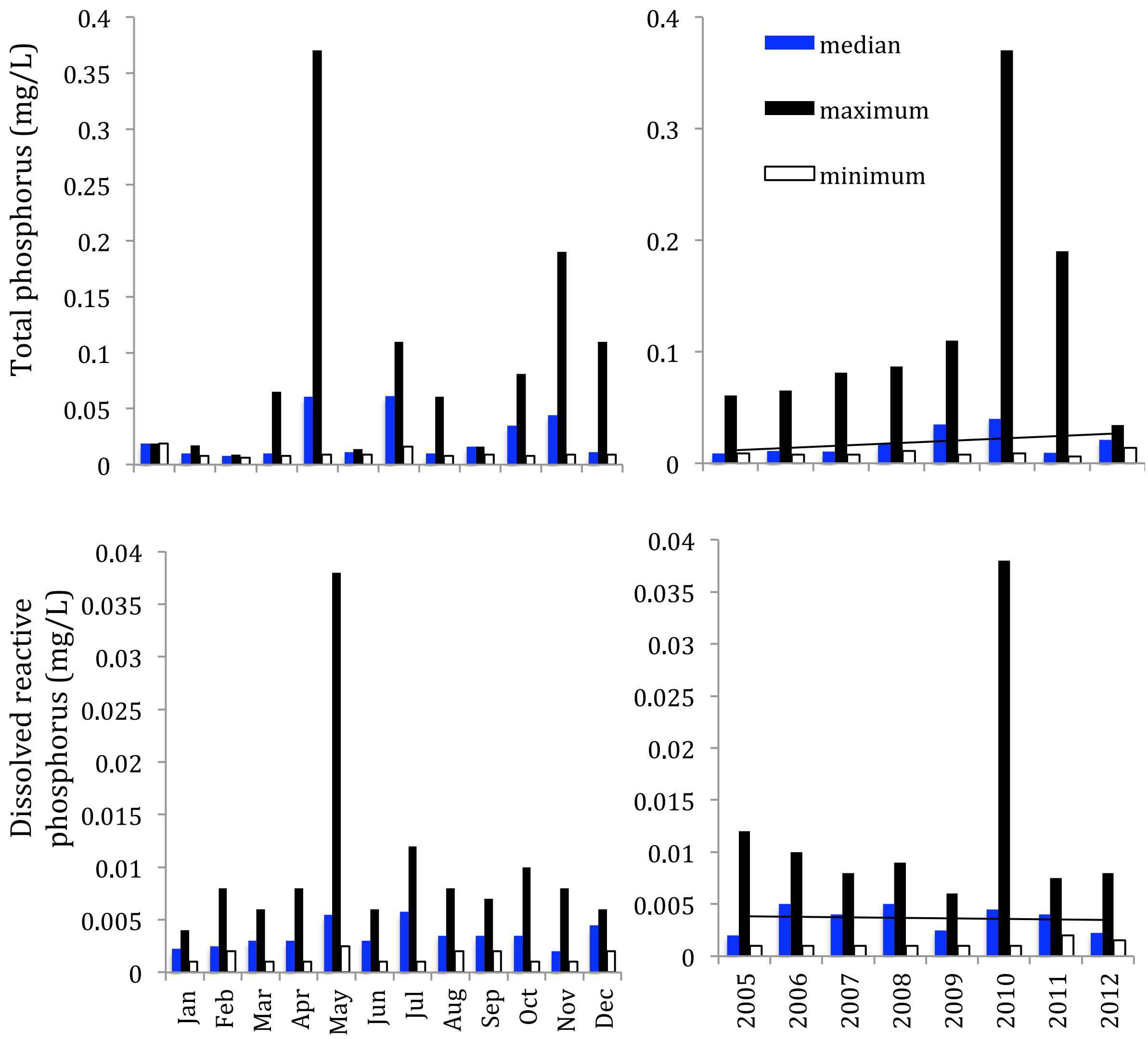


Figure 3.12: Minimum, median, and maximum monthly and annual concentrations for total nitrogen, nitrate + nitrite nitrogen, ammonia nitrogen, total phosphorus, and dissolved reactive phosphorus for the past 7 years and 10 months at the SH1 site on the Hurunui River (data sourced from Environment Canterbury).

The relationship between river flow and the concentration of total nitrogen, nitrate + nitrite nitrogen, and ammonia nitrogen is shown in Figure 3.13. There was no statistically significant relationship between flow and these three parameters. There was a positive relationship between flow and total phosphorus and dissolved reactive phosphorus concentration (Figure 3.14). As flow increases, total phosphorus and dissolved reactive phosphorus increases. Concentrations were typically lower at lower flows than at higher flows.

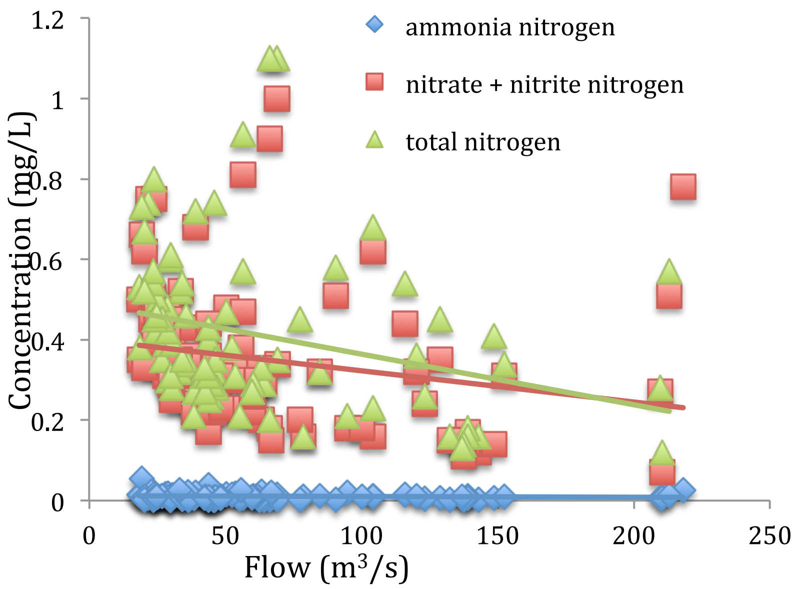


Figure 3.13: Relationship between river flow (m^3/s) and ammonia nitrogen, nitrate + nitrite nitrogen, total nitrogen concentration at the Hurunui River at SH1 over the last 7 years and 10 months (data sourced from Environment Canterbury).

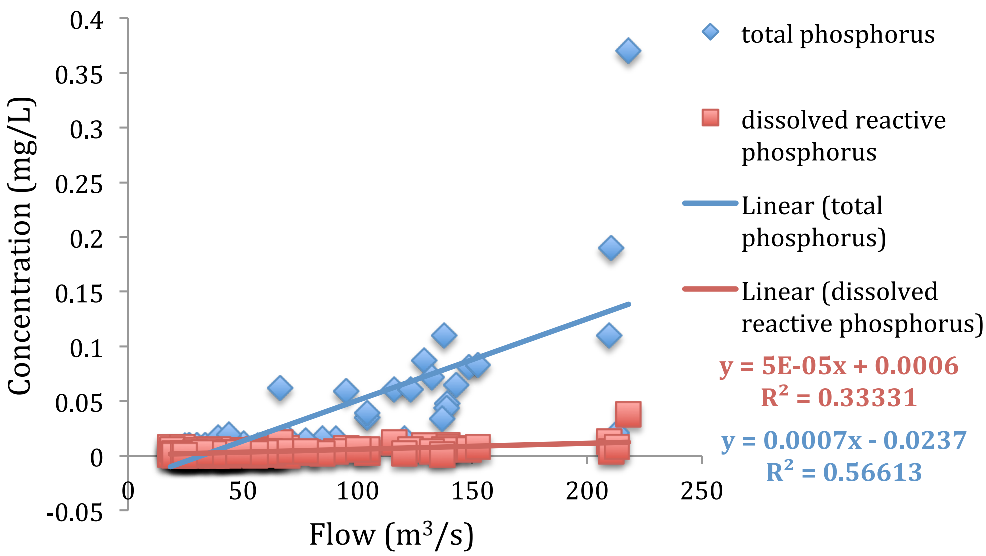


Figure 3.14: Relationship between river flow (m^3/s) and total phosphorus and dissolved reactive phosphorus at the Hurunui River at SH1 over the last 7 years and 10 months (data sourced from Environment Canterbury).

3.4.2 Nutrients interpretation and discussion

There have been variable seasonal trends in nutrient concentration at the SH1 site on the Hurunui River from 2005 to 2012. The maximum monthly values for all of the nutrients except for nitrate + nitrite nitrogen occurred in May. The maximum values for nitrate + nitrite nitrogen occurred in August. The monthly median concentration of total nitrogen and nitrate + nitrite nitrogen was the highest during late summer and early autumn. Median monthly total phosphorus concentration varied throughout the year, and median monthly dissolved reactive phosphorus concentration was the greatest during the winter. There was a minimal amount of variation in the median concentration of ammonia nitrogen throughout the year.

The seasonal nutrient concentration trends in the Hurunui River over the past 7 years and 10 months have been related to the seasonal trends in river flow. The positive relationship between total phosphorus and dissolved reactive phosphorus concentrations with river flow during this period was probably due to the increased runoff during times of high rainfall (Hayward *et al.,* 2003; Heathwaite & Johnes, 1996). Similar seasonal trends in nutrient concentrations have also been observed in the Waipara River. Elevated concentrations of total nitrogen, total phosphorus, and dissolved reactive phosphorus were related to high river flow (Hayward *et al.,* 2003). However, at the SH1 site, it appears that over the past 7 years and 10 months total nitrogen, nitrate + nitrite nitrogen, and ammonia nitrogen concentration have not been related to river flow. However, nitrogen and nitrate + nitrite nitrogen concentration were highest during the late summer and early autumn when river flow was at its lowest. Prior to 2001 there were no seasonal trends in nutrient concentration at the SH1 site (Hayward, 2001). This may be because nutrient concentrations vary throughout the year due to a number of factors including: rainfall, river flow, land use variation throughout the year, and periphyton biomass (Hayward, 2001; Heathwaite & Johnes, 1996). Compared to the nutrient results for other rivers around New Zealand, and internationally (Heathwaite & Johnes, 1996; Interlandi & Crockett, 2003; Scottish Environment Protection Agency, 2012), the existence of seasonal trends in nutrient concentrations in the Hurunui River was not unexpected.

As well as seasonal trends in nutrient concentrations, there has been a temporal trend in ammonia nitrogen concentrations at the SH1 site. There has been a decrease in ammonia nitrogen concentration from 2005 to 2012. This nutrient has fluctuated from increasing and decreasing trends in the past depending on the time period (Ausseil, 2010). This trend over the past 7 years and 10 months in ammonia nitrogen corresponds to the ongoing decrease in this nutrient in the Canterbury Region from 1998 to 2007, which suggests that there has been an improvement in water quality (Ballantine *et al.,* 2010). This improvement may be related to the change in farm management practices regarding effluent. Recently, the concentration of dissolved reactive phosphorus concentration in the Pahau River has reduced (Environment Canterbury, 2011c), but there has been no change in the concentration of this nutrient in the lower Hurunui River over the past 7 years and 10 months. From 1989 to 1999 total nitrogen, nitrate + nitrite nitrogen, and dissolved reactive nitrogen concentration increased at SH1 (Ausseil, 2010), and an increase in nutrients at the SH1 site on the Hurunui River has been detected as far back as 1989 (Brown *et al.,* 2011; Hayward, 2001). Over the past 7 years and 10 months there has been no change in the concentration of total nitrogen, nitrate + nitrite nitrogen, total phosphorus, and dissolved reactive phosphorus despite the increase in agriculture. This may be due to the change in farm management practices that have reduced the runoff of nutrients and prevented the concentration of nutrients from increasing in the river. When assessing the overall trend in water quality in a river over a period of time, more than one nutrient must be considered.

As well the trends in nutrient concentration at the SH1 site on the Hurunui River from 2005 to 2012, nutrients have fluctuated from year to year due to a range of possible factors. Past records have shown that ammonia nitrogen fluctuated between increasing and decreasing trends from 1989 to 1999 (Hayward, 2001), so yearly fluctuations in nutrient concentrations may be relatively normal. 2008 and 2010 had high maximum values of most of the nutrients and had a reasonably high flow compared to some of the other years. Therefore it is likely that there is a relationship between annual flow and some nutrient concentrations at this site, especially phosphorus.

Temporal trends in water quality are a result of a complex range of factors including land use, climate, human activities, and hydrologic processes (Interlandi & Crockett, 2003). Since anthropogenic activities and changes in the flow regime of a river can influence the concentration of nutrients, these must be identified in order to adequately understand both short-term and long-term trends in nutrient concentrations (Interlandi & Crockett, 2003). The greatest influence on nutrient concentration temporal trends is river flow (Hayward, 2001). Total phosphorus and dissolved reactive phosphorus at the SH1 site on the Hurunui River from 2005 to 2012 have been more strongly related to river flow than the nitrogen species. It has been identified that the Hurunui River, especially the lower reach, has been modified by water abstraction for irrigation. As a result, there has been a reduction in the mean monthly flows and the mean daily minimum flows during the irrigation season (Mosley, 2002). It is also highly likely that nutrients in the Hurunui River have been influenced over time by anthropogenic activities such as: an increase in agriculture, an increase in surface runoff, poor riparian protection, high nutrient loadings from the tributaries, and direct access to waterways by stock (Ausseil, 2010; Hayward, 2001). Water quality is also affected by climatic factors. Climate change is likely to complicate the interpretation of temporal trends in water quality (Interlandi & Crockett, 2003). It is probable that these anthropogenic activities and climatic factors will continue to have a large influence on the temporal trends of nutrient concentrations in this river.

Water quality parameters and nutrient concentrations over the past 7 years and 10 months have been higher compared the concentrations observed between August 1993 to June 1999 (Environment Canterbury data) and June 1989 to December 1999 (NIWA data) (Hayward, 2001) (Appendix 3).

Elevated nutrient levels in the ocean are often a result of high nutrient input from rivers, and this can result in phytoplankton blooms (Bintz *et al.,* 2003). While elevated levels of nutrient inputs into the coastal environment can enhance coastal productivity, the effects in the long term tend to be negative. If nutrient levels are elevated enough, the impacts in terms of marine biota and ecosystems can be significant (Caddy, 2000). Since many rivers discharge into the coastal environment, any change that occurs in the river catchment especially with regard to water quality, can have significant follow on impacts on the health of the coastal environment (Bintz *et al.,* 2003).

There have been a number of changes in the Hurunui River catchment over the past few years, especially with regard to land use. Many farms in the Hurunui River catchment, especially in the Culverden Basin converted to dairy in the early 1990s (McClintock *et al.,* 2002). Since the intensification of agriculture, water quality in the Hurunui River has declined (Ausseil, 2010). From 2002 to 2012, dairy cattle numbers in Canterbury increased by 73%, compared to 15% nationally (Saunders & Saunders, 2012). The number of dairy farms in Canterbury increased by 46% between 2000 and 2010, compared to a 17% decrease nationally. To mitigate the runoff of nutrients to the waterways, irrigation practices have recently changed from mostly border dyke irrigation to spray irrigation (Brown *et al.,* 2011). Mitigation measures have also been put in place especially with regard to farm management practices to reduce nutrient runoff. These mitigation measures have included: riparian protection, reduction in fertiliser application, reduction in the use of feed containing high levels of nitrogen, reduced winter grazing, and improved management of effluent (Brown *et al.,* 2011). These measures appear to have been successful since most of the nutrients over the past 7 years and 10 months have not significantly increased in concentration at the SH1 site on the Hurunui River.

Although river water quality varies across rivers in New Zealand, there is an overall decreasing trend in water quality (Ballantine *et al.,* 2010). The poorest water quality in New Zealand is in rivers that originate in the lowlands and rivers that flow through areas with urban and pasture land use (Ballantine *et al.,* 2010; Larned *et al.,* 2004). Conclusions on the overall health of rivers in a region is difficult to determine as some parameters show an increasing trend in water quality, while others show a decreasing trend. For instance, from 1998 to 2007 in rivers in the Canterbury Region, there was an increase in conductivity and oxidised nitrogen, indicating degradation in water quality, but a decrease in ammonical nitrogen, indicating an improvement in water quality. Nationally, from 1998 to 2007, an increase in conductivity, total nitrogen, and total phosphorus indicated a degradation of water quality (Ballantine *et al.,* 2010). It is likely that there will be a decline in the health of the Hurunui River, especially at the river mouth if greater water availability allows the continuation of land use intensification (Jellyman & Harding, 2011).

Water quality in countries such as Scotland and the United States of America also varies depending on the land use and changes that have occurred in river catchments (Interlandi & Crockett, 2003; Scottish Environment Protection Agency, 2012). Similar to New Zealand, water quality trends have varied across these countries. The concentration of some nutrients such as ammonical nitrogen has reduced as a result of the increase in river flow and improved catchment management. Like New Zealand, rivers with the poorest water quality in these countries tend to be in areas that are associated with urban and farmland areas (Interlandi & Crockett, 2003; Scottish Environment Protection Agency, 2012).

3.5 Water temperature, pH, and dissolved oxygen

As well as nutrient concentrations, chemical and physical characteristics of water are also measured in order to assess the health of a waterway (Hayward, 2001; Hayward *et al.,* 2003). This typically includes the measurement of pH, water temperature, conductivity, dissolved oxygen, and turbidity (Hayward *et al.,* 2003). A range of factors drives variation in these parameters. The chemistry of the water can be indirectly influenced by the concentration of nutrients in the water. While nutrients have a control on periphyton growth, this can influence the water chemistry especially pH (Ausseil, 2010). This is because algal production can alter the carbon dioxide/bicarbonate equilibrium (Ausseil, 2010). The pH of a waterway also depends on the geology of the catchment (Hayward *et al.,* 2003). Water temperature is important as organisms become stressed in temperature outside of their tolerance ranges (Bintz *et al.,* 2003; Mosley, 2002). It is also important as it can influence photosynthesis and respiration of primary producers, and the decomposition of organic matter (Bintz *et al.,* 2003). Water temperature also has follow on effects on other water quality variables such as dissolved oxygen concentration (Ongley, 1996). Sewage and other discharges, air temperature, water abstraction, and bankside shading affect water temperature (Hockey *et al.,* 1982; Ministry for the Environment, 2011). Conductivity is affected by periphyton growth, river flow, and the geology of the river catchment (Hayward *et al.,* 2003). Dissolved oxygen varies with: river flow and water turbulence, water temperature, salinity, atmospheric pressure, and photosynthetic activity (Hayward *et al.,* 2003; Ministry for the Environment, 2011; Ongley, 1996).

River flow, the concentration of nutrients, and the chemical and physical characteristics are important not only to the river itself, but to the coastal environment also. This is because rivers and streams provide a pathway from the terrestrial environment to the marine environment (Smith *et al.,* 1999).

3.5.1 Water temperature, pH, and dissolved oxygen results

The following results are based on data collected from January 2005 to October 2012 at the SH1 site on the Hurunui River. This is equal to 7 years and 10 months.

The median monthly pH at the SH1 site on the Hurunui River over the past 7 years and 10 months has ranged from 7.7 in July to 8.1 in January (Figure 3.15). The monthly maximum and minimum pH values varied more than the median monthly values. The highest maximum monthly pH occurred in December and the lowest monthly minimum occurred in July. The lowest monthly minimum values for pH occurred in May and July. The difference between the monthly median and monthly maximum pH was the smallest during the winter. The annual median pH has ranged from 7.8 in 2006, 2009, and 2010 to 8.3 in 2005. There has been no change in the annual median pH over the past 7 years and 10 months. The highest annual maximum pH occurred in 2005. There was more variation between the minimum and maximum pH values in 2005 compared to the variation in 2012.

The median monthly dissolved oxygen concentration from 2005 to 2012 ranged from 10.1 mg/L in January to 12.3 mg/L in June (Figure 3.15). Dissolved oxygen concentration was the highest in the winter and lowest in the summer. The highest maximum monthly dissolved oxygen concentration occurred in August, and the lowest monthly minimum in February. The annual median dissolved oxygen concentration ranged from 10.3 mg/L in 2008 to 12.4 mg/L in 2004. There has been no change in the annual median dissolved oxygen concentration over the past 7 years and 10 months. The highest annual maximum occurred in 2009.

Over the past 7 years and 10 months, the median monthly water temperature has ranged from 7°C in June, to 17.8°C in February (Figure 3.15). Water temperature was the highest during summer and lowest during winter. The highest maximum monthly water temperature occurred in January, and the lowest monthly minimum in June. The annual median water temperature ranged from 8°C in 2004 to 14.7°C in 2008. There has been no change in the annual median water temperature over the past 7 years and 10 months. Variation in water temperature between years has been minimal.

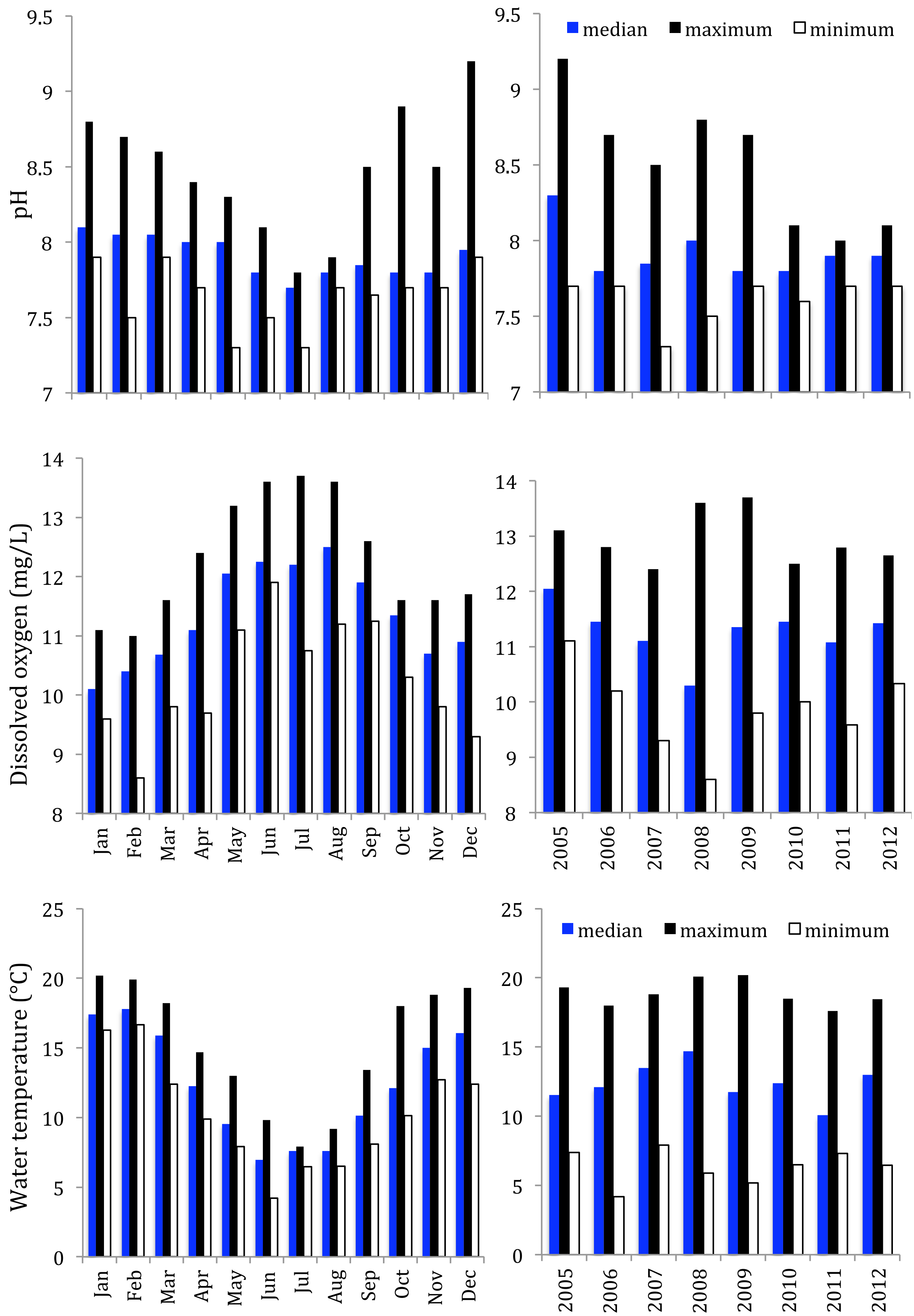


Figure 3.15: Minimum, median, and maximum monthly and annual values for pH, dissolved oxygen and water temperature at the SH1 site on the Hurunui River over the past 7 years and 10 months (data sourced from Environment Canterbury).

From 2005 to 2012, there was an inverse relationship between water temperature and dissolved oxygen (Figure 3.16). As water temperature increased, dissolved oxygen concentration decreased. The relationship between dissolved oxygen concentration and water temperature was greater compared to dissolved oxygen and river flow.

There was a weak relationship between flow and dissolved oxygen concentration (Figure 3.17). As flow increases, the water gets more stirred up, which causes more oxygen to be taken up from the air.

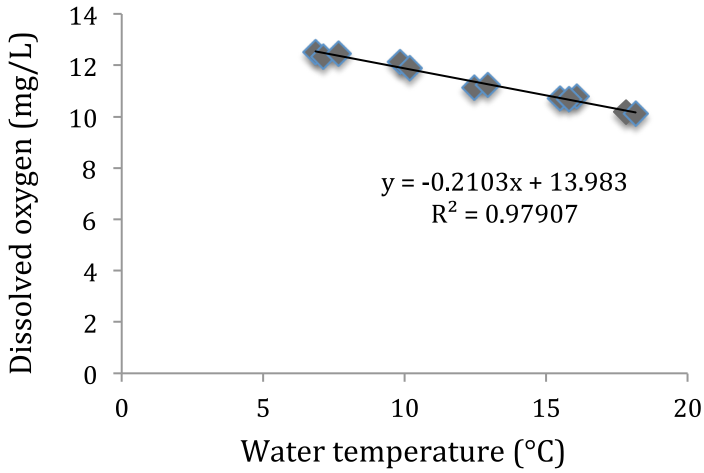


Figure 3.16: Mean monthly water temperature and mean monthly dissolved oxygen at the SH1 site on the Hurunui River from over the past 7 years and 10 months (data sourced from Environment Canterbury).

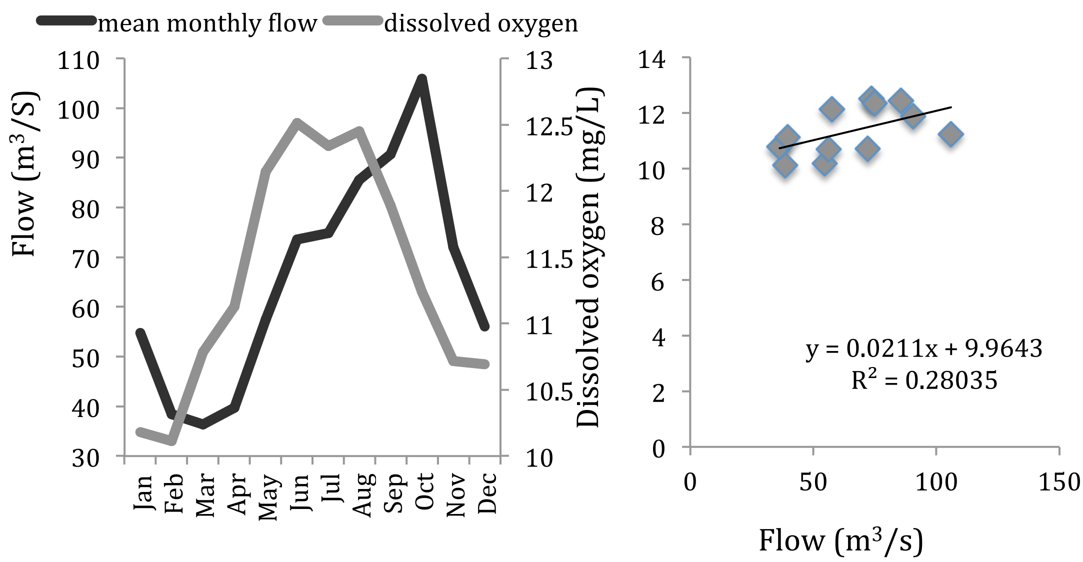


Figure 3.17: Mean monthly flow and mean monthly dissolved oxygen at the SH1 site on the Hurunui River from 2005 to 2012 (left). River flow vs dissolved oxygen at the SH1 site on the

Hurunui River over the past 7 years and 10 months (right) (data sourced from Environment Canterbury).

3.5.2 Water temperature, pH, and dissolved oxygen interpretation and discussion

There are distinct trends in pH, dissolved oxygen concentration, and water temperature through the year. The trends in these parameters from 2005 to 2012 were similar to those from previous years for the Hurunui River (Hayward, 2001). The pH and water temperature were highest in the summer when flow was at its lowest, and lowest during the winter when flows were generally at their highest. It is possible that the pH at the SH1 site on the Hurunui River is influenced by periphyton, especially in the summer since periphyton growth can be a problem during the summer months at this site (Mosley, 2002). Dissolved oxygen had the opposite trend, where the lowest values were during the summer and the highest values during the winter. This seasonal trend in dissolved oxygen was expected since the solubility of dissolved oxygen increases with flood related aeration of water, and with a decrease in water temperature (Hayward *et al.,* 2003; Ongley, 1996). Of these parameters, water temperature maximum, mean, and minimum values varied the least between the months. For dissolved oxygen, monthly minimum concentrations varied more than the monthly mean and maximum concentrations. This may have been due to the influence that periphyton growth can have on both dissolved oxygen and water pH (Hayward *et al.,* 2003).

As well as monthly trends, there were yearly differences in pH, dissolved oxygen, and water temperature. The median values of these parameters did not change over the past 7 years and 10 months. Water pH and dissolved oxygen concentration in the lower Hurunui River in the past has decreased (Hayward, 2001). Although these parameters have fluctuated from year to year, they have remained stable from 2005 to 2012. Water temperatures in the Waipara River, also in North Canterbury, fluctuate from year to year in response to weather conditions (Mosley, 2003), so the yearly variation in temperature at the SH1 site on the Hurunui River is not unusual.

Temporal trends in water quality data depend on the time scale (Snelder & Scarsbrook, 2005). Short-term trends are typical, whereas longer trends are usually not so evident (Ballantine *et al.,* 2010; Snelder & Scarsbrook, 2005). Although there has been fluctuation from year to year in water parameters from 2005 to 2012 at the SH1 site on the Hurunui

River, long-term trends have been minimal. Long-term trends are best assessed when there is at least 10 years of data (Stevenson *et al.,* 2010). In an analysis of water quality at the National River Water Quality Network (NRWQN) sites in New Zealand, there were different trends depending on the time period. Over the 19-year period, all of the nutrients increased, but over a 10-year period only two of the nutrients had an increase. Water quality trends were also stronger at the NRWQN sites over a 5-year period compared to a 10-year period (Ballantine *et al.,* 2010). This demonstrates the caution that must be applied when assessing temporal trends in water quality.

Like nutrients, temporal trends in pH, dissolved oxygen, and temperature can be difficult to determine as they can be affected by both anthropogenic and natural hydrological and climatic changes in the flow regime (Hayward, 2001; Interlandi & Crockett, 2003; Snelder & Scarsbrook, 2005). It is possible that the water quality of the SH1 site on the Hurunui River over the past 7 years and 10 months has been influenced by these interacting factors, making the exact cause for the variability in water quality difficult to determine. Despite the lack of any obvious long-term trends, short-term changes can be valuable for detecting potential changes of greater magnitude (Hayward, 2001).

3.6 Limitations and errors

While the data record for mean daily flow over the past 7 years 10 months is relatively complete, there are limitations in the data for both nutrients and other water quality parameters. Some months and years do not have records for each nutrient and water parameter. As a result, the analysis of both seasonal and temporal trends in water quality is limited. Despite the inconsistent record, comparisons have been made with data analysed from earlier time periods. Assessment of trends in flow regime and water quality over the past 10 years and 11.5 months years has been limited because of ENSO, Pacific Decadal Oscillation, and climate change, and anthropogenic activities such as water abstraction.

3.7 Summary

This chapter outlined both the monthly and yearly trends in river flow, nutrient concentrations, and water quality parameters over approximately the past 10 years and 11.5 months for flow, and the past 7 years and 10 months for the other parameters at the SH1 site on the Hurunui River. The lowest flows at this site occur over the summer, although flood events were not uncommon during the summer. The highest flows were in the spring, and there appeared to be little change in the yearly flows over the past 10 years 11.5 months.

There were variable trends in nutrient concentrations and other water quality parameters and both tended to be related to river flow. In general, the highest nutrient concentrations as well as pH and temperature tended to be when the river flow was at its lowest during late summer and autumn. Seasonal trends were also more evident than yearly trends.

Although there are seasonal trends in the significant wave height along the east coast of New Zealand, these trends are weak (Pickrill & Mitchell, 1979). The dominance of waves with a significant wave height of 1.5-2.0 m arriving from the south over the past 13 years has been typical of the wave climate along the east coast of New Zealand.

Chapter 4: Sediment processes

4.1 Introduction

Sediment processes were investigated in this study, and this included suspended sediment, sediment composition, and sediment deposition. These three aspects were investigated since they are interrelated and are all influenced by river flow (Nichols & Boon, 1994). For instance, the concentration of suspended sediment can be influenced by the amount and composition of deposited fine sediment on the hapua bed, especially when the deposited sediment is fine and wind driven circulation is significant. The composition of sediment along the shore of a water body can reveal information about the energy in the area since the deposition of sediment is directly related to the energy in the area (Haslett, 2008).

These three aspects also can have considerable implications for biota, as well as for the concentration of contaminants. Suspended sediment is of interest in riverine environments as it influences: primary production by controlling the amount of light that penetrates the water, the feeding and behaviour of aquatic biota, the pathways of adsorbed contaminants, the bathymetry by directly influencing rates of accretion and erosion, and physical properties of the water such as temperature (Prandle, 2011; Ryan, 1991; Sedell *et al.,* 1990; Wood & Armitage, 1997). Sediment also has a control on the chemical reactivity and biological productivity, hence why it is important to understand sediment processes in coastal lagoons (Nichols & Boon, 1994). Particles smaller than 62 µm readily adsorb chemicals (Ongley, 1996), so any change in the deposition of fine sediment within the hapua can have numerous implications. Excess fine sediment can also accumulate if there is an increase in suspended sediment, and this can then alter the composition and diversity of entire biotic communities (Clapcott *et al.,* 2011).

This chapter is divided into five sections. Methods are in section 4.2, results in section 4.3, an interpretation and discussion of the results in section 4.4, limitations in section 4.5, and a summary in section 4.6. Sections 4.2, 4.3, and 4.4 are divided into three subsections for suspended sediment, sediment deposition, and sediment composition. An integrated discussion of the results is reserved for Chapter 9 after the presentation of water parameters in Chapter 5, nutrient results in Chapter 6, and short-term and long-term changes in the hapua behaviour and geomorphology in Chapter 7.

This chapter addresses the following research objectives:

- to examine suspended sediment concentrations in different areas of the hapua and in different energy conditions,
- to examine substrate composition in different areas of the hapua, and
- to determine where the majority of the sediment is transported, deposited and transferred to within the hapua system.

4.2 Methods

4.2.1 Suspended sediment

4.2.1.1 Principles and practices

There are a number of direct and indirect methods for measuring the concentration of suspended sediment in riverine environments (Chapman, 1996; Pavanelli & Bigi, 2005). Of the direct methods, the gravimetric method is the most common. This involves taking water samples which are then filtered in order to determine the total suspended sediment weight in a specific volume of water from a specific time and place (Chapman, 1996; Marquis, 2005; Pavanelli & Bigi, 2005; Pereira *et al.,* 2009). Water samples can be either taken with a depth-integrated sampler (Ongley, 1996), or alternatively with an automatic water sampler (Phillips *et al.,* 2000). Automatic water samplers can significantly reduce sampling effort, however there are often limitations. For instance, during low river flows, the concentration of suspended sediment can be inaccurate due to the small size of the sample, and the cost of the equipment is often high (Phillips *et al.,* 2000). To determine the overall amount of suspended sediment, samples can be filtered, centrifuged, or left to settle and the resultant supernatant water siphoned off. Centrifuging is considered to be the most accurate, but it requires expensive specialised equipment and can be logistically challenging if the samples need to be centrifuged in the field (Ongley, 1996).

Indirect methods for measuring suspended sediment include the use of instruments such as: an acoustic Doppler current profiler (ADCP), sedimeters, laser *in situ* scattering, transmissiometry (LISST), and the measurement of turbidity in Nephelometric Turbidity Units (NTU). All require regular calibration to ensure their accuracy (Pavanelli & Bigi, 2005; Thomas & Ridd, 2004; Wall *et al.,* 2006). The measurement of turbidity is often a common approach for indirectly measuring suspended sediment (Chapman, 1996; Marquis, 2005). Turbidity is the scattering and absorption of light by the particles in the water (Chapman, 1996; Parlimentary Comissioner for the Environment, 2012). Turbidity is not always suitable to use as a proxy for suspended sediment as it is not only related to suspended sediment, but also to other particulates such as phytoplankton, and tannins in the water (Marquis, 2005; Parlimentary Comissioner for the Environment, 2012). Biological activity, pH and surface runoff can also influence turbidity (Chapman, 1996). Although a relationship between turbidity and suspended sediment can occur, the relationship is often poor, especially with an increase in particle size (Thomas, 1991). Turbidity can also be an unreliable proxy for suspended sediment as it typically varies between streams and seasons (Canadian Council of Ministers of the Environment, 2002).

Suspended sediment can also be indirectly measured with an ADCP. These are increasingly being recognised as a useful tool for measuring suspended sediment, especially in monitoring programmes (Schoellhamer & Wright, 2003). The advantage of using an ADCP for suspended sediment concentration is that it can be measured continually over a specific time period (Schoellhamer & Wright, 2003). The echo intensity recorded by the ADCP can be used as a proxy for suspended sediment concentration. The difference between the emitted signal and the returning signal is partially related to the concentration of particles in the water (Kim & Voulgaris, 2003; Merckelbach & Ridderinkhof, 2006).

Despite the advantages, there are many disadvantages associated with measuring suspended sediment concentration with an ADCP (Schoellhamer & Wright, 2003). Firstly, the geometrical spreading of the acoustic wave bundles and a reduction of the signal by the water can alter the returning signal (Merckelbach & Ridderinkhof, 2006). Secondly, determining suspended sediment concentration from an ADCP involves a series of complex equations to convert acoustic intensity to suspended sediment concentration (Kim & Voulgaris, 2003). ADCP measurements can also be affected by bio fouling and variations from particle reflectivity (Schoellhamer & Wright, 2003). Suspended sediment concentrations derived from an ADCP tend to be underestimated compared to concentrations measured from water samples when the size of the sediment is small, and the opposite effect is observed when the sediment is larger in size (Ghaffari *et al.,* 2011). The colour of the sediment also affects the returning signal, with lighter particles reflecting more light compared to darker particles. Although particularly useful in hazardous environments and water bodies where suspended sediment concentration can change rapidly, the use of ADCP must be carefully evaluated for each situation (Schoellhamer & Wright, 2003).

Sediment traps can be used to give an indication of the difference in suspended sediment between different areas. However, these have had limited success in fluvial environments due to their alteration of the flow hydrodynamics, and the dependence of the trap efficiency on the density, size and concentration of the sediment and the current direction and velocity (Thomas & Ridd, 2004).

The Ministry of the Environment has developed protocols for assessing sediment in New Zealand streams. However, these protocols are specific to wadeable streams, and are not ideal for use in hapua for a number of reasons. Firstly, river flow is often too great for measurements to be taken across the width of the water body. Secondly, the depth of the water in hapua is usually too deep to take measurements across the water body. Although there have been studies on suspended sediment in coastal lagoons (Douillet *et al.,* 2001; Lopes *et al.,* 2001), as yet there have been no protocols developed specifically for monitoring suspended sediment in these systems.

4.2.1.2 Sample collection

Because of the complex calibration procedures and the unsuitability of the indirect methods (Ghaffari *et al.,* 2011), it was deemed preferable to measure suspended sediment from water samples in this study.

As identified in Chapter 2, suspended sediment samples were collected at five sites throughout the hapua (refer to Figure 2.7 in Chapter 2). These samples were collected in two low energy events, during two floods, and during a storm. Samples in the low energy events and the floods were also taken at high, mid, and low tide. Because of the safety concerns during the storm and the wave overtopping occurring for only a few hours over high tide, samples were not taken at different stages of the tide in the storm.

Samples for suspended sediment were taken in low energy conditions on the 13th of May 2012 when the mean daily river flow was 37 m^3/s and the outlet was at the northern end of the hapua (Figure 4.1a). The backshore site was labelled B1 and the outlet site was labelled O1. A second low energy event was sampled on the 24th of September 2012 when the river flow was 59 m^3/s and the outlet was at the southern end (Figure 4.1b). The backshore and outlet sites were labelled B2 and O2 respectively.

Samples were taken on the 25th of June 2012 just after the flood peak when the mean daily river flow was 147 m^3/s and the outlet was at the northern end (Figure 4.1c). The backshore and outlet sites were labelled B3 and O3 respectively. A second flood was sampled on the 9th of August 2012 when the mean daily river flow was 221 m^3/s and the outlet was at the southern end (Figure 4.1d). The backshore and outlet sites were labelled B4 and O4 respectively.

Samples were taken during a storm on the 7th of November 2012 when waves were arriving at the Canterbury wave buoy from the south to south south-east and the significant wave height was around 2.75m, and the river flow was 67 m^3/s. The outlet was at the southern end of the hapua during the storm (Figure 4.1e). The backshore and outlet sites were labelled B5 and O5 respectively.

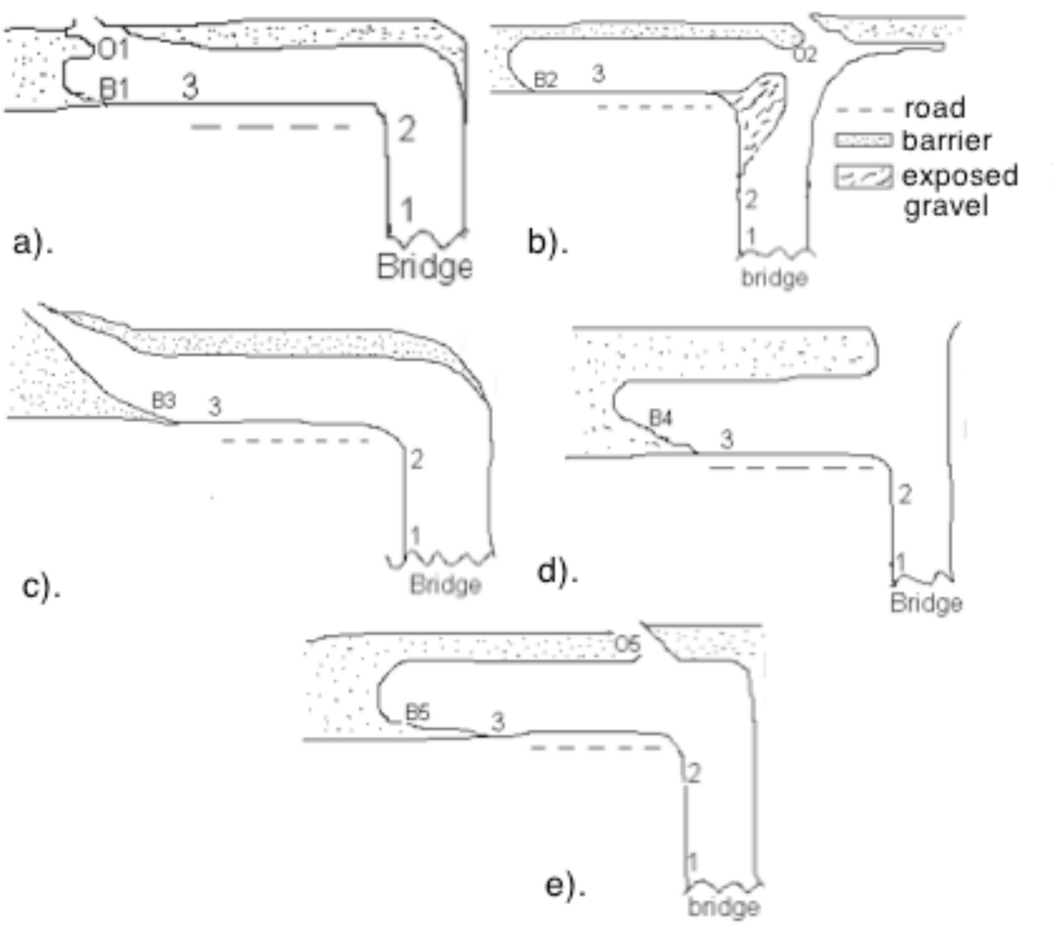


Figure 4.1: Sketches of the antecedent morphology at the time of sampling and the location of the sample sites (not to scale), a) corresponds to low flow conditions on the 13th of May 2012, b) to low flow conditions on the 24th of September 2012, c) to flood conditions on the 25th of June 2012, d) to flood conditions on the 9th of August 2012, and e) to a storm on the 7th of November 2012.

A depth-integrated water sampler was used to take a water sample vertically throughout the water column (Figure 4.2). This was taken from a position where the fieldworker was standing at knee depth in the water. This was to ensure safety, especially in the flood and storm events. Samples were taken up flow of the fieldworker to ensure that any disturbed sediment did not enter the sample. Three 1 L samples were taken (two minutes apart) from each of the five sites every 2 to 3 hours over an outgoing tidal cycle. At the same time, three replicates of water parameters were taken, two minutes apart. This was to reduce variability in the results and the chance of an incorrect reading. The samples were taken in order from sites O to B and then 3 to 1, since the sites closest to the outlet were the most likely to be influenced by the tide induced change in lagoon water level. Site 1 upstream in the river was likely to be the least impacted from the tides.

Each site took approximately 10 to 15 minutes to sample. However, due to the time taken to walk to some of the sites, it took approximately 1.5 to 2 hours to sample the five sites. Samples were transferred from the sample bottle in the integrated water sampler to a clean plastic 1 L bottle. This sampling approach using the integrated water sampler was deemed the most appropriate and accurate as it allowed for isokinetic sampling (Ongley, 1996), and it took into account the variation in suspended sediment throughout the water column (Ghaffari *et al.,* 2011). This gave an overall averaged suspended sediment concentration for the vertical profile. An automatic water sampler was not used as it would have been restricted to only one of the five sample sites. The use of the integrated water sampler as opposed to the automatic water sampler also ensured that all of the samples were taken in the same way.

Sediment traps were deployed at sites 1, 2, 3, and B (Figure 4.2). Details of the date of deployment, and the river flow at the time are in Appendix 5. Because of the directional flow of the river flowing through the hapua, the opening of the traps was orientated directly into the flow of the river. Each trap was anchored to the bottom of the hapua so that the water just covered the trap. The mesh size of the sediment trap bag was 100 μm in size. Each trap was left deployed for about the same amount of time, approximately 6 hours.

Figure 4.2: Integrated water sampler (left) and deployed sediment trap right).

4.2.1.3 Sample and data processing

The collected water samples were processed in the laboratory. Samples were filtered through a Watman 45 mm preweighed filter, and dried at 60°C for at least 24 hours. The filters were reweighed to give the final weight of sediment per litre. Data was processed in *Microsoft Excel* to compare the average suspended sediment at each site, at each stage of the tidal cycle (high tide, mid tide, low tide), and in different energy conditions. The post-hoc least significant difference test was carried out in *IBM Statistics 19 (SPSS).*

After the traps were collected, the sediment was washed out of the bags in the laboratory and dried in an oven at 60°C for at least 24 hours. The final weight of sediment was processed in *Excel* to give the mean weight of sediment at each site. Where required, post hoc statistical analyses were carried out in *SPSS.*

4.2.2 Sediment deposition

4.2.2.1 Principles and practices

A wide range of methods have been developed to measure sediment accumulation which range from simple measurements using a ruler, to the use of sophisticated equipment such as optical back scatters and surveying of the riverbed (Parlimentary Comissioner for the Environment, 2012; Thomas & Ridd, 2004). Many of the methods for measuring sediment accumulation have limitations as they often alter the flow dynamics of the surrounding water column (Thomas & Ridd, 2004).

4.2.2.2 Sample collection and data analysis

After a flood event there was a significant amount of fine sediment deposited along the shore. To measure sediment accumulation, three transects were laid out from the waterline to the high water mark defined by the debris line at each site. 20 points were chosen by generating a random number for the distance along the transect, and then another random number for the final point away from the transect. The depth of the deposited sediment was then measured using a ruler placed vertically into the sediment (Figure 4.3). The results were processed in *Microsoft Excel* to compare the depth of deposited fine sediment between the sites, and also the amount of variation within each site.

Figure 4.3: Method using a ruler to measure sediment depth.

4.2.3 Sediment composition

4.2.3.1 Principles and practices

There have been a number of methods developed to measure sediment composition depending on the size of the sediment. These methods can include: grain size comparators for field determination, sieving, image analysis, electroresistance particle size analysers, laser diffraction, and sedimentation methods (Table 4.1) (Simons & Sentürk, 1992; Syvitski, 1991). Because of the impracticality of taking a large sample back to the lab, larger gravels are typically assessed in the field with field sieves and grain size comparators. However, most sediment samples are taken back to the lab where they are assessed for size (Syvitski, 1991). The most appropriate method depends on the size of the sediment, or on time constraints and expenses.

Table 4.1: Size ranges and techniques for sediment analysis (√ = technique applicable, x = limited applicability). Adapted and sourced from (Syvitski, 1991, p.5).

Particle	**Size**	**Technique**					
		Count	**Sieve**	**Settling from the top**	**Settling from suspension**	**Laser scatter**	**Photon correlation spectroscopy**
Gravel	>2mm	√	√	X	X	X	X
Sand	2mm - 63μm	√	√	√	X	√	X
Silt	63μm - 2μm	√	√	√	√	√	X
Clay	<2μm	X	X	√	√	X	√

4.2.3.2 Sample collection

Sediment samples were taken once from each of the sites to allow for sediment composition to be determined. Details of the sample dates are in Appendix 6. Sieve analysis was deemed the most appropriate for this study since the purpose was to determine the percentage of different sized sediment, and because of the size of the sediment at the study site. A transect was laid out at each site from the waterline to the debris line as close to low tide as possible so that the maximum amount of substrate was exposed. Three sediment samples were taken from each site, one as close to the water as possible, one at the debris line and the third midway between the waterline and the debris line. Samples were collected with a hand shovel from the top 10 cm and placed in a labelled container for later analysis in the laboratory. When there was large gravel present, it was separated from the smaller sized sediment and weighed in the field.

4.2.3.3 Sample and data processing

Samples were processed in the laboratory based on the techniques detailed by Lewis and McConchie (1994). Firstly, the sediment samples were dried in an oven at 60°C for at least 2 days. Each sample was placed through a range of sieves, down to a size of 4 ϕ and sieved for 12 minutes. Some of the sites, especially site 3 along the backshore of the main part of the hapua had a significant amount of gravel-sized limestone that had originated from the limestone outcrops along the backshore. These samples were not ideal to sieve as the mechanical action of sieving would have eroded the limestone, making the overall percentage of larger particles under represented and smaller particles over represented. Therefore these samples were not sieved, instead they were visually assessed for the approximate percentage of gravels and sands. Sediment that was -4 ϕ or larger was separated into different categories, while sediment smaller than this size was not separated, instead was grouped into one category classified as fines.

The data was analysed in *Microsoft Excel* to see if the percentage of different sized sediments varied with distance from the waterline. Data was also analysed to see whether there was a difference in the sediment size composition between the sites.

4.3 Results

4.3.1 Suspended sediment

Water samples were collected for suspended sediment analysis in low energy conditions the 13th of May and the 24th of September 2012, on the 25th of June and the 9th of August 2012 in flood conditions, and on the 7th of November 2012 during a storm when waves were breaking over the hapua barrier. Unfortunately due to safety concerns, samples were unable to be taken from site O during the floods.

4.3.1.1 Low energy conditions

There was a difference in the amount of suspended sediment in the two low energy events. On the 13th of May 2012, the suspended sediment ranged from 0.0019 g/L at site O1, to 0.0035 g/L at site 1 (Figure 4.4). The concentration of suspended sediment on the 24th of September 2012 ranged from 0.015 g/L at site 1 to 0.069 g/L at site 3. Analysis of variance showed that the variation between the sites in both of the low energy events was not significant ($P>0.05$).

There was no observable trend in the mean suspended sediment between high, mid, and low tides at each of the sites in both of the low energy events. In the first low energy event sites 1 and B1 had an increase in suspended sediment from high to low tide (0.0018 g/L to 0.0059 g/L at site 1 and 0.0014 g/L to 0.0039 g/L at site B1); alternatively sites 2, 3, and O1 had a slight increase in suspended sediment from high to mid tide and then a slight decrease from mid to low tide (0.0023 g/L to 0.0022 g/L at site 2, 0.0030 g/L to 0.0023 g/L at site 3, and 0.00182 g/L to 0.00178 g/L at site O2). In the second low energy event there was a minimal difference from high to low tide at sites 1, 2, and O2 (0.010 g/L to 0.016 g/L at site 1, 0.022 g/L to 0.019 g/L at site 2, and 0.009 g/L to 0.036 g/L at site O2), but a large difference at difference stages of the tide at sites 3 and B2 (0.058 g/L to 0.143 g/L at site 3 and 0.0075 g/L to 0.009 g/L at site B2).

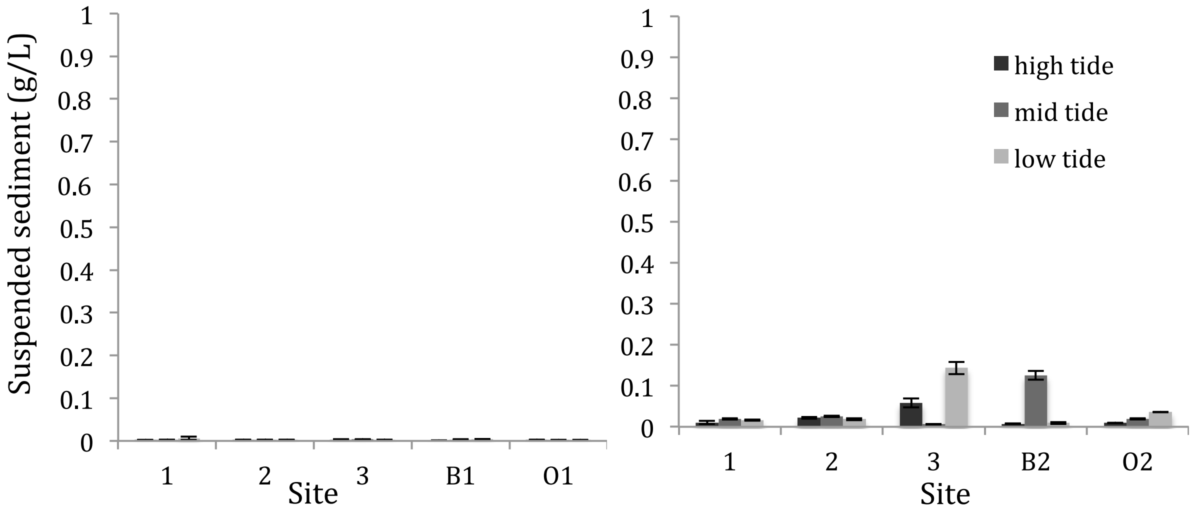


Figure 4.4: Mean suspended sediment at each of the sites at high, mid, and low tide during low energy event 1 on the 13th of May 2012 with error bars (left), and low energy event 2 on the 24th of September 2012 with error bars (right).

4.3.1.2 Flood conditions

The concentration of suspended sediment was much higher during the flood events (mean 0.298 g/L and 0.466 g/L) compared to the low energy events (mean 0.0027 g/L and 0.035 g/L) and was significantly different ($P<0.01$ (Figure 4.5).

Suspended sediment varied between the sites during the flood events ($P<0.05$). A least significant difference (LSD) test showed which sites had a similar concentration of suspended sediment. In the first flood, sites 1 and B3 were similar (0.185 g/L and 0.171 g/L), and sites 2 and 3 were similar (0.391 g/L and 0.443 g/L). Sites 1 and B3 had about half the amount of suspended sediment compared to the other two sites. Suspended sediment also varied between the sites during the second flood ($P<0.05$). The LSD test showed that sites 1 and 2 had a similar mean concentration of suspended sediment (0.865 g/L and 0.790 g/L), and sites 3 and B4 were similar (0.108 g/L and 0.10 g/L). The mean concentration at sites 1 and 2 was much higher compared to sites 3 and B4. At all of the sites during the flood events there was a decrease in concentration of suspended sediment from high to low tide.

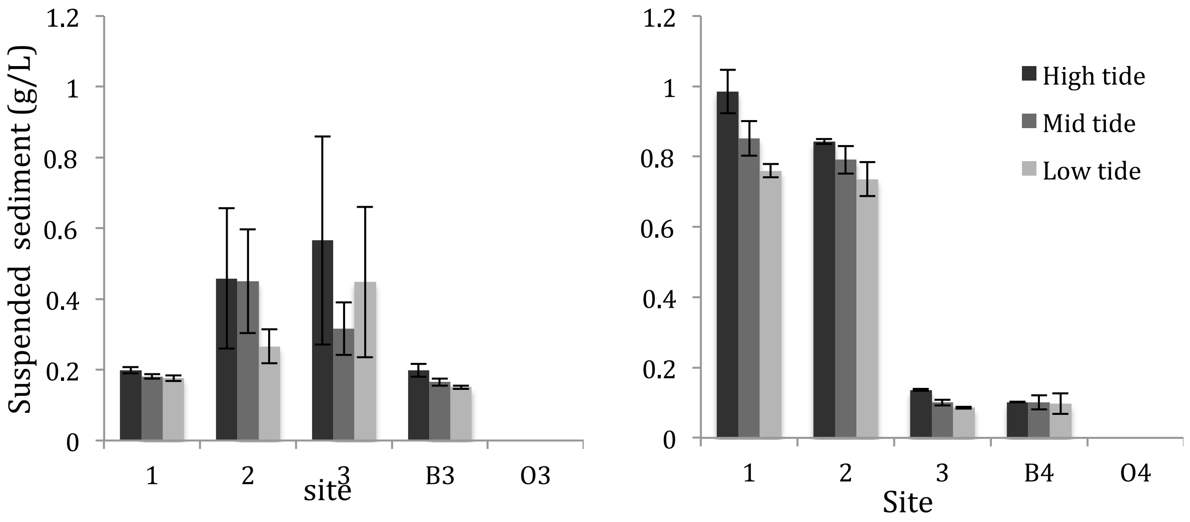


Figure 4.5: Mean suspended sediment at each of the sites at high, mid, and low tide during flood 1 on the 25th of June 2012 with error bars (left) and flood 2 on the 9th of August 2012 with error bars (right).

4.3.1.3 Storm conditions

Suspended sediment during a storm on the 7th of November 2012 ranged from 0.018 g/L at site 2 to 0.319 g/L at site O5 (Figure 4.6). There was no spatial variation in suspended sediment (P>0.05).

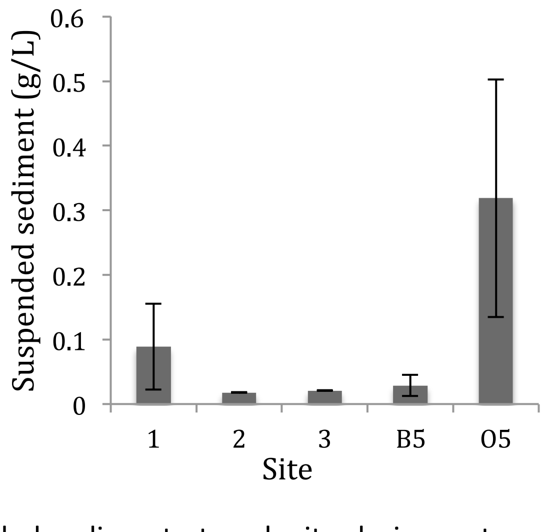


Figure 4.6: Mean suspended sediment at each site during a storm on the 7th of November 2012 with error bars.

4.3.2 Sediment deposition

After the flood on the 25th of June 2012, a significant amount of fine sediment was deposited along the shoreline of the hapua (Figures 4.7 and 4.8). The mean daily flow of the flood was 145.6 m^3/s. The depth of fine sediment on the surface of the lagoon bed was measured at each site close to high tide after this flood at sites 2, 3 and B. Site 1 was unable to be sampled due to the substrate being covered by the river, and site O was unable to be sampled due to the safety concerns of being close to the outlet. The depth of fine sediment was measured to examine the amount of fine sediment that can be deposited along the shoreline of the hapua on the falling limb of a flood.

Figure 4.7: Deposited fine sediment along the hapua shore after a flood.

Figure 4.8: Deposited fine sediment along the shoreline at site B after a flood on the 25th of June 2012.

The depth of fine sediment on the surface of the lagoon bed initially increased with distance away from the waterline at site 2 to a maximum depth of 140 mm around 300 cm away from the waterline (Figure 4.9). The depth of this sediment then decreased towards the high water mark. At site 3, the depth of fine sediment decreased with distance away from the waterline (Figure 4.10). There appeared to be no observable trend in the depth of sediment away from the waterline at site B, although the depth of fine sediment was slightly less at the high water mark (Figure 4.11). The sediment was relatively evenly distributed at this site.

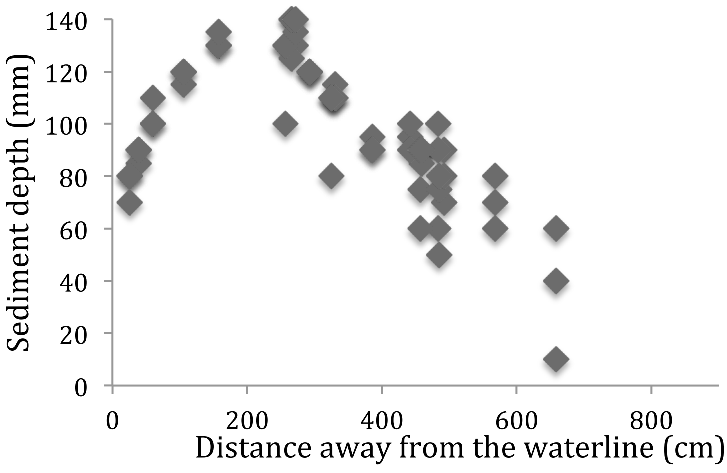


Figure 4.9: Depth of fine sediment on the hapua bed vs distance away from the waterline at site 2 after a flood.

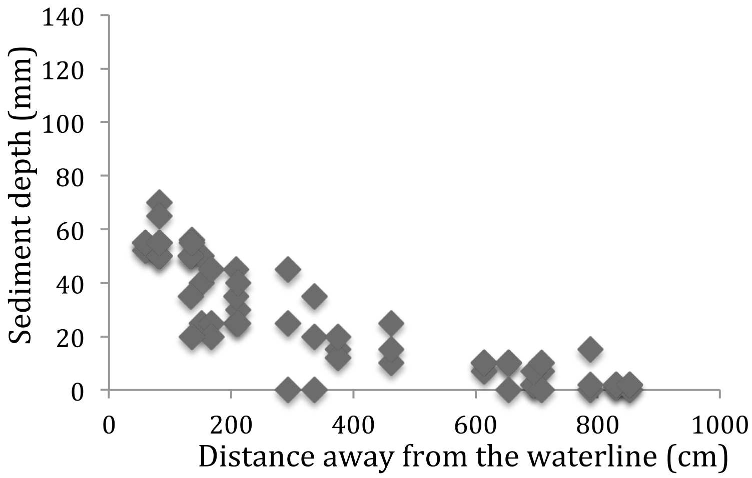


Figure 4.10: Depth of fine sediment on the hapua bed vs distance away from the waterline at site 3 after a flood.

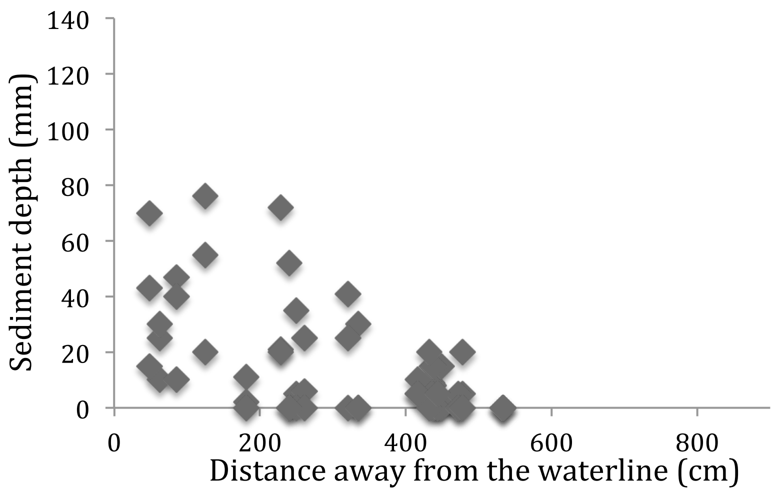


Figure 4.11: Depth of fine sediment on the hapua bed vs distance away from the waterline at site B after a flood.

The depth of fine sediment visibly reduced with distance away from the shoreline between sites 3 and B where the shoreline was composed of cobbles (Figure 4.12). After a second, larger flood, there was a minimal amount of fine deposited sediment along the shoreline compared to the first flood event.

Figure 4.12: Deposited fine sediment along the shore between sites 3 and B (closest to the shore at the left and furthest from the shore at the right).

The mean depth of deposited fine sediment on the hapua shoreline varied between the sites after a flood event (Figure 4.14). Site 2 had a mean sediment depth of 95 mm, whereas sites 3 and B had a much lower amount of sediment deposited, with around 20 mm of deposited fine sediment.

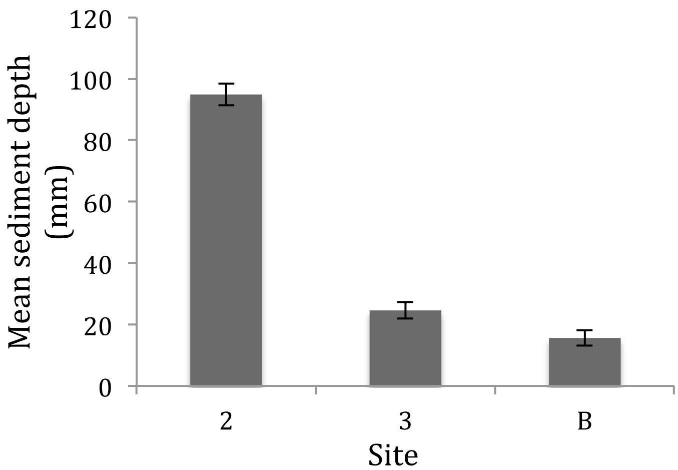


Figure 4.13: Mean fine sediment depth on the hapua bed after a flood at sites 2, 3, and B with error bars.

4.3.3 Sediment composition

Sediment samples were taken from each site so that the composition both within each site and between sites could be compared. Sites 2 and O had a decrease in sediment size away from the waterline. Alternatively, there was a minimal amount of variation in the composition of sediment with distance away from the waterline at sites 1 and B.

The composition of sediment at O varied with distance from the water (Figure 4.14). The larger sediments (around -1 Φ) were present closer to the waterline. Virtually no sediment smaller than 1.5 Φ was present at the waters edge. The distribution of different sized sediment became more even with distance away from the water. Site Ob (midway between the water and the debris line) and Oc (debris line) had a range of different sized sediments, with a slightly greater dominance of smaller sized sediments at site Oc compared to site Ob.

The composition of sediment also varied with distance from the water at site 2 (Figure 4.15). More than half of the sample at the waterline consisted of sediment -2 Φ or larger. Site 2b consisted of sediment -2 Φ or larger, and sediments 3 Φ or smaller. There was a small amount of sediment in the -1 Φ to 2 Φ size ranges at this site. The majority of sediment at site 2c was 4 Φ or smaller. Only a small percentage (5%) was -3 Φ in size.

Sediment samples were only taken at the waters edge at sites 1 and B, and both sites showed the same trend in sediment composition (Figure 4.16). This was because of the inability to collect samples at site B away from the waterline because of the presence of large boulders, and because of the even substrate at site 1. Approximately 80% of the sediment at both sites was -4 Φ or larger.

After the flood event, a layer of fine sediment covered sites 2, 3, and B. This sediment was smaller than 4 Φ in size. The absence of sand indicates that the river flow was not great enough to transport sand along the shoreline (Nichols, 2009).

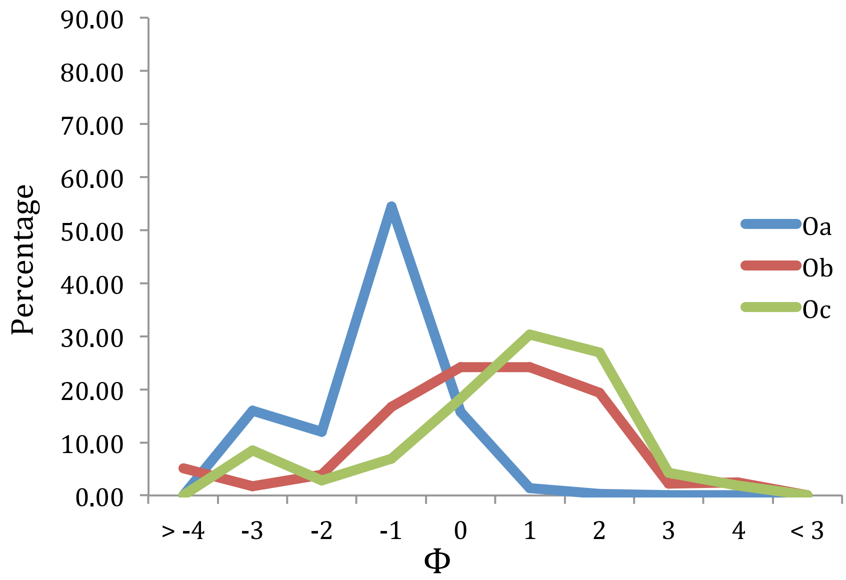


Figure 4.14: Sediment size composition on the surface of the hapua shoreline at site O.

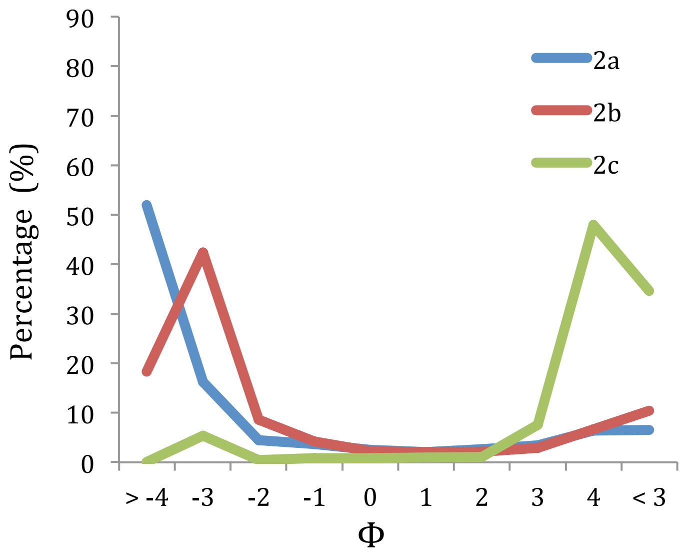


Figure 4.15: Sediment size composition at site 2 on the surface of the hapua shoreline.

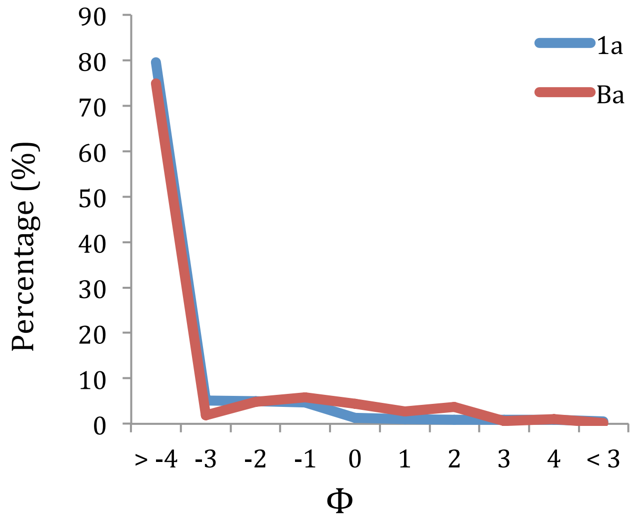


Figure 4.16: Sediment size composition at sites 1 and B on the surface of the hapua shoreline.

4.4 Interpretation and discussion of results

4.4.1 Suspended sediment

As expected, the concentration of suspended sediment concentration was much greater at all of the sites during the floods compared to the low energy events and the storm. While the concentration of suspended sediment in low energy conditions at all of the sites was below 0.07 g/L, the concentration was much higher during flood conditions. For the first flood event, suspended sediment ranged from 0.2 g/L at site 1 to around 0.4 g/L at site 3. During the second flood event the mean suspended sediment concentration ranged from around 0.1 g/L at sites 3 and B1 to around 0.85 g/L at site 1. During the storm, the mean suspended sediment was less compared to the flood, and ranged from 0.018 g/L at site 2 to 0.319 g/L at site O5. Sites 1 and O5 were variable in the suspended sediment concentration during the storm.

While it is evident that suspended sediment fluctuates at this hapua in response to the energy conditions, other factors can influence levels over longer time periods. Suspended sediment is related to land use and will often increase if there is an increase in soil erosion, landslides, or anthropogenic activities such as agriculture and mining (Ryan, 1991; Wood & Armitage, 1997). Since suspended sediment is related to catchment activities, changes in the river catchment must be identified and taken into account when assessing the potential changes that dam or irrigation developments could have on suspended sediment loads at the hapua.

Suspended sediment loads in rivers across New Zealand are highly variable (Hicks *et al.,* 1996). The highest suspended sediment yields are in rivers originating in the Southern Alps on the west coast of the south island and in the rivers located at the East Cape in the north island (Hicks *et al.,* 1996). While it is evident that some fine sediment is deposited along the shore of this hapua, visual observations during floods identified that a large amount of sediment is also transported into the ocean. It is also likely that some fine sediment circulates around the hapua by wind driven circulation, and currents resulting from the regular rise and fall in lagoon water level in response to the tide.

Not only did suspended sediment vary between the energy conditions, but it also varied between the sites. The greatest spatial variation in suspended sediment was during the floods and storm. There was a minimal amount of variation during the low energy conditions. The spatial variation during the floods was most likely due to the configuration of the outlet, which had a direct influence on the flow of water through the hapua. During the first flood event, the river was flowing through the hapua and exiting through an outlet at the northern end of the hapua. As a result, the concentration of suspended sediment at each of the sites was similar. Alternatively, during the second flood event the outlet was located at the southern end of the hapua. As a result, there was little to no flow through the main part of the hapua. This explains the marked difference in suspended sediment at sites 1 and 2 compared to sites 3 and B2. It also demonstrates the influence of river discharge on the concentration of suspended sediment. This relationship between suspended sediment concentration and high river discharge is also typical for estuaries (Caffrey & Day, 1986). During the second flood and the storm, the outlet was located at the southern end of the hapua. However, the spatial variation in suspended sediment was less in the storm compared to the flood. This would have been due to the disturbance of the hapua bed and the contribution of sediment from the barrier as storm waves entered the hapua. Therefore it is concluded that the greatest concentration of suspended sediment and the greatest amount of spatial variation occurs during flood events when the outlet is at the southern end of the hapua.

While the spatial variation in suspended sediment can be explained to some extent by the shape of the hapua, it cannot explain all of the observed spatial trends. For instance, during the first flood, sites 1 and B3 had a similar concentration of suspended sediment but very different flows. It is possible that the higher flow at site 1 washed away the sediment, whereas the slower flow at site B3 allowed the suspended sediment to fall out of suspension and settle on the hapua bed. The moderate flow at sites 2 and 3 may have resulted in these sites having the highest concentration of suspended sediment as it was neither washed away nor deposited on the hapua bed.

In a study conducted in the Ria de Aveiro Lagoon in Portugal, it was identified that suspended sediment, temperature and salinity decreased with distance from the river system (Lopes *et al.,* 2001). The concentration of suspended sediment in estuaries also typically varies spatially, with higher concentrations further upstream from the outlet (Prandle, 2011). Suspended sediment in estuaries is often variable due to factors such as tides and wind (Dronkers, 1986). The typical decrease in suspended sediment towards the outlet or inlets of coastal lagoons is because of the influence of saltwater which causes fine sediment to coagulate and precipitate (Bird, 1994). However, due to the minimal influx of seawater at high tide, this is unlikely to occur in this type of coastal lagoon, especially when the river flow is high. It is highly likely that the suspended sediment concentration at the outlet of this hapua depends on the river and wave conditions, the outlet morphology, and the location where the sample was taken rather than the influence of seawater. Visual observations showed an increase in suspended sediment at the outlet when there was strong river flow through a well formed elongated outlet channel. It was evident that the converging water and accelerated flow of water caused the hapua bottom near the mouth of the lagoon to erode, leading to an increase in suspended sediment. During the storm there was a lot of suspended sediment at the outlet and this was due to the disturbance of the hapua bed by the waves. Rather than suspended sediment at the outlet being controlled by seawater, it is concluded that the shape of the outlet, the wave conditions, and the river flow control the concentration of suspended sediment.

Estuaries and coastal lagoons, like this hapua, can have dynamic spatial and temporal patterns in suspended sediment that change over time depending on the dominant influence. Suspended sediment can change in response to tides, river discharge and wind

(Caffrey & Day, 1986; Douillet *et al.,* 2001; Kjerfve & Magill, 1989; Lopes *et al.,* 2001; Powell *et al.,* 1989). There appeared to be no tidal influence on suspended sediment in both low energy conditions and floods at this hapua. The lack of tidal influence on suspended sediment during the floods was most likely due to the significant water flow at all of the sites and the turbulent mixing of the water. Although there was a slight decrease in concentration from high to low tide during the floods, this may have been due to sampling occurring on the falling limb of the flood. While it is expected that there would be a minimal amount of tidal influence on the concentration of suspended sediment during floods due to the high river flow, the absence of any change in the concentration of suspended sediment during low energy conditions from high to low tide indicates that there is a minimal tidal influence on the concentration of suspended sediment in this system. The outlet was sampled during low energy conditions, but the difference in suspended sediment from high to low tide was minimal. This may have been due to the constant wave action at the mouth at all stages of the tidal cycle, and also because of the narrowing of the river as it went through the outlet, hence ensuring a strong river flow and causing the sediment to remain unaffected by the tide related change in lagoon water level.

Suspended sediment can also be influenced by wind driven circulation in coastal lagoons (Caffrey & Day, 1986; Douillet *et al.,* 2001; Kjerfve & Magill, 1989; Lopes *et al.,* 2001; Powell *et al.,* 1989). For instance, during the second low energy event, there was an increase in suspended sediment around mid tide in response to wind driven resuspension of fine sediment from the bottom of the hapua. This was especially evident at site 3. This demonstrates that there can be wind driven circulation and disturbance of the substrate in this hapua, with follow on effects on the concentration of suspended sediment and nutrients such as phosphorus. The amount of suspended sediment in response to wind driven circulation will depend on the sediment composition and the amount of deposited resuspendible sediment on the bottom of the hapua. While mixing of the water column is unlikely to cause vertical stratification (Smith, 1994), it is likely that suspended sediment varies across the hapua when wind driven circulation is significant. Wind driven circulation has been shown to influence both spatial and temporal distributions of suspended sediment concentrations in estuaries (Caffrey & Day, 1986), although the effects tend to be greater in larger coastal lagoons where the prevailing wind is in alignment with the longitudinal axis of the lagoon (Smith, 1994). While tides can influence suspended sediment concentrations in estuaries and coastal lagoons (Douillet *et al.,* 2001; Dronkers, 1986; Kjerfve & Magill, 1989; Vale & Sundby, 1987), the effect within this hapua is considered to be minimal, instead wind action and river flow are considered to be the major influences on suspended sediment.

Suspended sediment is important as it can alter other water quality parameters. For instance, water temperature can decrease as the concentration of suspended sediment increases (Ryan, 1991). However it is likely that water temperature in this hapua is not primarily controlled by suspended sediment, but instead by river flow as there was no relationship between suspended sediment and temperature during this study.

Suspended sediment is also important as it has implications for biota and available habitat. An increase in suspended sediment can have a range of negative impacts on aquatic invertebrates, fish and primary producers (Ryan, 1991; Sedell *et al.,* 1990; Wood & Armitage, 1997). The reduction in light penetration as suspended sediment increases can reduce primary production. If primary producers are impacted by suspended sediment, the community will also be affected since invertebrates and fish species are dependent on primary producers (Wood & Armitage, 1997). Suspended sediment can also alter the available habitat for fish species and benthic organisms if it settles out of suspension and deposits on the riverbed. Some organisms are reliant on the interstitial spaces between larger sediments for refuge and for laying eggs (Clapcott *et al.,* 2011). It is likely that the biota currently present in this hapua are adapted to the dynamic environment where suspended sediment loads are variable due to river flow and the shape of the hapua. With a more stable river flow and a reduction in flood frequency and magnitude, suspended sediment would possibly reduce (Batalla *et al.,* 2004; Ericson *et al.,* 2006; Willis & Griggs, 2003). Both positive and negative impacts of this scenario on biota could occur. A reduction in suspended sediment could possibly benefit biota by reducing the negative impact of clogging of their feeding apparatus and more light penetration for primary producers. Alternatively, negative impacts from a reduction in suspended sediment could lead to an increase in water temperature outside of the tolerance ranges of organisms. Any change that does occur in the concentration of suspended sediment will inevitably result in an alteration in the behaviour and composition of biota within the hapua (Ryan, 1991).

Because of the negative implications of suspended sediment, some countries have developed guidelines for the concentration of suspended sediment in rivers. Currently, there are no specific guidelines for monitoring suspended sediment in rivers in New Zealand. Guidelines for suspended sediment in Canada state that during a short-term exposure period resulting from anthropogenic activities, suspended sediment concentration must not exceed any more than 25 mg/L over the clear flow baseline levels (Canadian Council of Ministers of the Environment, 2002). For periods longer than a month, suspended sediment concentrations must not exceed more than 5 mg/L over the baseline levels. The guidelines for high flow events are different; when the background concentration is 25-250 mg/L, an increase due to anthropogenic activities must not be more than 25 mg/L, and if the background concentration is over 250 mg/L then there must not be more than a 10% increase (Canadian Council of Ministers of the Environment, 2002). The Canadian guidelines take into account the amount of time that biota can be exposed to elevated levels of suspended sediment until they become harmed. It is evident the concentration of suspended sediment is influenced by the shape of the hapua, therefore this must be taken into account if baseline levels are to be developed.

4.4.2 Sediment deposition

The deposition of fine sediment varied between the sites that were sampled. Site 2 had the most amount of deposited fine sediment, and had an initial increase in deposited fine sediment away from the shoreline to where the maximum depth occurred around 300 cm from the waterline. The most amount of sediment deposition at this site was probably due to the lower slope and greater shoreline area compared to the other sites. This would have allowed for the water movement to be less, resulting in the settling of more fines. In general, the smaller the slope, the greater the amount of fine grained sediment deposition (Nichols, 2009). The trend in sediment depth at site 2 was likely to have been influenced by the slight rise about 2-3 m from the waterline, resulting in the maximum amount of fine sediment deposition. Site 3 had a decrease in fine sediment depth away from the waterline, and there appeared to be no major trend at site B. Visual observations of the shoreline between sites 3 and B showed the same trend as site 3. The trend in sediment depth at site 2 was likely to have been influenced by the slight rise in elevation of the shore about 2-3m from the waterline. This would have influenced the flow dynamics, resulting in the maximum amount of fine sediment deposition. The absence of a trend in fine sediment depth with distance from the water at site B was likely due to the bed topography where there was a dominance of coarse boulders along the shore.

Like suspended sediment, deposited sediment is also of concern due to the direct impacts on aquatic biota (Clapcott *et al.,* 2011; Ryan, 1991). Both the amount of sediment deposition, and the size of the deposited sediment are important. The effects of a change in sediment deposition on biota can be variable, with possible impacts on: community composition, diversity, abundance, invertebrate feeding and growth, and invertebrate behaviour (Clapcott *et al.,* 2011). If a change in the flow regime causes the amount of deposited fine sediment to increase, the feeding apparatus of both invertebrates and fish may become clogged (Ryan, 1991), and suitable habitat vital for protection from predators may be reduced or eliminated (Sedell *et al.,* 1990). Any change in fine sediment deposition would impact benthic biota and community composition. However, since this hapua is a dynamic environment, it is likely that the present biota is adapted to variable levels of deposited fine sediment. Because no studies have been done on the aquatic vegetation and invertebrates in this hapua, the effect of a change in sediment deposition on biota cannot be determined.

Guidelines have recently been developed to assess and monitor deposited sediment in wadeable streams in New Zealand (Clapcott *et al.,* 2011). Macro invertebrates are currently widely used as an indicator of in-stream health since they are directly impacted by sediment. Recommended guidelines have been developed in New Zealand for sediment cover, substrate size, and suspendible sediment, with the guidelines varying depending on the in-stream value, whether it is biodiversity, salmonid spawning habitat, or amenity. For biodiversity and fish habitat, it is recommended that there be no more than 20% cover of fine sediment or 450 g/m^2 compared to other substrate classes. For stream amenity, there should be no more than 25% cover of sediment (Clapcott *et al.,* 2011). As yet, no guidelines have been developed specifically for hapua.

The amount of fine sediment deposited within this hapua will depend on the dominant processes at the time. There are four sediment processes that have been identified in coastal lagoons: erosion, transport, deposition and accumulation, and sediment diagenesis and consolidation (Figure 4.17) (Nichols & Boon, 1994). Depending on the process, sediment will either be exported from the system, modified by things such as animals, or act as a sink that can then subsequently act as a feedback source of sediment. The sediment processes at one time will depend on the relative influence of external factors such as river inflow, waves, wind, and tides (Nichols & Boon, 1994).

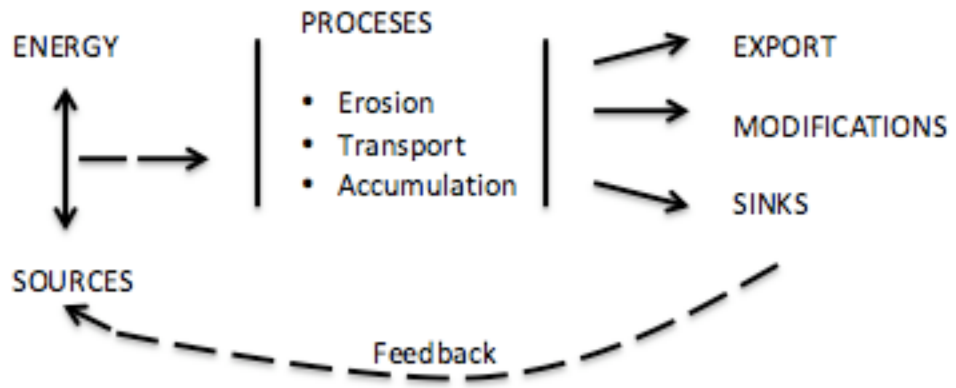


Figure 4.17: Relationship between sediment energy and sources with processes and the resultant export, modification, and sinks of sediment (Nichols & Boon, 1994, p.163).

The difference in fine sediment deposited along the shore of the Hurunui River hapua shows that fine sediment can be rapidly redistributed and altered, especially in periods of high river discharge. After the first flood, there was a large amount of sediment deposited along the shore of the hapua. However, after the second flood the majority of the fine sediment was scoured away (Figure 4.18). This demonstrates that sediment deposition is dependent on the size of the flood. Kirk (1991) states that a significant amount of fine sediment is deposited in the lagoon on the falling limb of a flood. While this is true for moderate floods, large floods in this hapua instead scour fine sediment from the bed of the lagoon resulting in an armoured lagoon bed. If flood magnitude were to reduce, it is possible that there would be an increase in the amount of sediment deposited along the shore of the hapua. This is because smaller floods deposit sediment, and larger floods deposit little. Because sediment deposition in this system is directly related to flow velocity (Ryan, 1991), deposited fine sediment will be resuspended once the flow velocity of the river reaches a critical value (Dronkers, 1986). Therefore it is evident that this hapua will have cycles of fine sediment deposition and removal depending on the river velocity. Any change in the amount of deposited fine sediment that does occur will influence the concentration of suspended sediment especially when wind driven circulation and disturbance of the hapua bed is significant.

Figure 4.18: Difference in the substrate at site 2 after a moderate flood (left) and after a larger flood (right).

4.4.3 Sediment composition

Sediment distribution is controlled by a number of factors such as: topography, sediment size, distance from the shoreline and the influence of tides and currents (Yaacob & Mustapa, 2010). The variation in sediment size both within a site, and between sites is usually due a combination of factors. Because of these interacting factors, the distribution of sediments in coastal lagoons and estuaries is often complex and challenging to decipher (Yaacob & Mustapa, 2010).

The size of sediment varied within most of the sites. Sites 2 and O showed a similar and expected trend where the size of sediment generally decreased with distance away from the waterline. The distribution of finer sediments away from the water line at site O near the river mouth can be explained indirectly from tidal action. Although this site is slightly affected by tidal backwater effects at high tide, this hapua does not experience a significant influence from the tides (Hart, 2009b). Tides indirectly influence the water level in the lagoon. The hydrostatic pressure on opposite sides of the barrier varies according to the stage of the tidal cycle (Hart, 1999). This constant rise and fall of the water level in the lagoon, as well as the river flow and sea-condition-related change in morphology, results in a difference in the composition of sediment near the outlet. Unlike estuaries, there is always a significant flow through the outlet so the water is never still. However, the in-wash of water during high tide and the change in lagoon water level results in this area being regularly covered and uncovered. The dominance of larger particles closest to the water, and the dominance of smaller sand particles further away from the water reflect the difference in energy conditions with distance away from the river channel.

The decrease in sediment size at site 2 with distance from the water was also likely to be attributed to the decrease in energy away from the water. Except for the debris line, the majority of the substrate was composed of sediment -2 Φ or larger. Only a small amount of sediment was smaller than -2 Φ. This reflects the environment that causes the substrate to be relatively armoured due to the high river flow, and the delivery of coarse sediment from the braided section just above this site.

Sites 1 and B did not show the expected reduction in sediment size away from the waterline. Only one sample was taken at each of these sites. Site B had an obvious increase in sediment away from the waterline. This was likely due to the small distance from the water to the backshore cliff (3 m), compared to 16.5 m at site 2. It is likely that this was also due to the contribution of boulders from the cliff. Only one sample was taken at the waterline as the rest of the shoreline was composed of sediment larger than 4 Φ, especially boulders. It was visually evident that there was a minimal amount of difference in the size of sediments away from the waterline at site 1.

Spatial differences existed between the sites and this was because of the difference in energy at each site. Like estuaries that have spatial differences related to the degree of fluvial and marine influences (Haslett, 2008), coastal lagoons are also likely to have spatial differences related to the relative influence of different processes. This coastal lagoon has spatial differences in sediment composition. Sites 1 and B are dominated by sediment -4 Φ or larger. While these sites can be classified as similar in terms of their sediment composition, they must not be considered the same in terms of habitat for biota. This is because of their different physical conditions such as temperature, flow and conductivity (Chapter 5). Sites 2 and O were dominated by smaller sediments compared to sites 1 and B. The waterline at site 2 was dominated by smaller sediments (-3 Φ) compared to site O that was dominated by sediment -1 Φ in size. The coarser sediments at the outlet are in agreement with results obtained by Yacoob and Mustapa (2010) where the presence of coarser particles is attributed to the stronger current and wave energy. River mouths typically have higher energy compared to other areas, preventing smaller particles from depositing, so usually have coarser sediment (Haslett, 2008).

Sediment in estuaries can come from three primary sources: glaciers or rivers, erosion of the estuary margins, or from outside of the estuary itself such as the ocean (Haslett, 2008). This can be applied to coastal lagoons also. Sediment in hapua can come from the ocean or barrier as waves wash over the barrier during sea storms, or from the river during floods (Kirk, 1991). It is likely that there is a third minor source of sediment in this system. The presence of limestone chips at site 3 indicates that erosion is occurring along the margins of this hapua. After a flood, there was a large amount of fine sediment deposited at sites 2, 3, and B. The absence of sand indicates that the river flow was not great enough to transport sand along the shoreline (Nichols, 2009). This highlights the influence of river flow on the composition of sediment at each site, and throughout the hapua. It is probable that the sediment composition at each site is not only dependent solely on the river flow, but also on sea storms, and the rate of erosion along the margins of the hapua.

The spatial differences in sediment composition at this hapua are consistent with studies that have also shown that there can be a difference in the composition of sediments at different locations within a coastal lagoon system (Lopes *et al.,* 2001). Unlike estuaries that typically have a reduction in sediment size toward the fringes (Carter, 1988), this study demonstrates that sediment composition throughout this hapua is highly variable and depends on the relative influence and dominance of a range of factors. The spatial variation in sediment of different sizes can have implications for biota, as well as the concentration of heavy metals (Nichols & Boon, 1994; Ongley, 1996). Fine cohesive sediments can adsorb heavy metals, so areas more dominated by fines have the potential to have higher concentrations. In a management context, it is evident that both within and between site variations in sediment must be considered.

4.5 Limitations and errors

Suspended sediment can be measured over time or in relation to river flow (Phillips *et al.,* 2000). Since the purpose of this study was to investigate the change in suspended sediment over a tidal cycle in a range of different energy conditions, samples were taken every 2 to 3 hours. More samples were not taken at a more regular time interval due to the logistical constraints of having a larger sample size. The results showed that the variation in the amount of suspended sediment in water samples taken at each site per sampling event was minimal. Although samples should have been taken across the river in order to account for any variation in suspended sediment across the river (Ongley, 1996), this was not possible due to safety concerns, the often swift river flow, and the depth of the lagoon. Instead, all samples were taken at knee depth from the shore.

Due to safety concerns and inaccessibility, site O was not sampled during the floods, however it is likely that the concentration would have been similar to the sites that were close to the main flow of the river.

Because of the time taken to get to each of the sites, samples were not taken exactly at high, mid, and low tide. Therefore the concentration of suspended sediment at different stages of the tide is an approximation. In order to take samples at each of the five sites at the same time, considerable sampling effort with extra equipment and people would be needed.

During the second low energy event the presence of a strong wind resulted in higher than expected concentrations of suspended sediment. Although this changed altered the suspended sediment concentrations, it also gave additional insight with regard to the processes that can occur within this system that can influence suspended sediment.

As well as the use of water samples to measure the mass of suspended sediment, sediment traps were also used. There were numerous inconsistencies and limitations with this method. Because of the change in lagoon level in response to the tide, the traps were often uncovered at low tide. Since they were deployed at high tide by hand, the depth that they were deployed at was limited. Also, they did not sample the entire water column, leading to biased results. As a result, the collected sediment would not have represented the entire vertical water column, instead representing the particular location in the water column where the trap was present.

While the results represent the amount of sediment deposited at each site after a flood, it is likely that the amount of deposited fine sediment varies depending on the size of the flood and the shape of the hapua. To determine whether this is the case or not, more measurements would need to be taken after a number of flood events.

Some of the sites were difficult to sample and each site was different in terms of the substrate and area along the shore. To take a series of samples away from the waterline at site 2, the river flow had to be reasonably low so that the riverbed was exposed. This resulted in the samples for site 2 being taken approximately two months after samples were taken from the other sites. As a result, the sediment composition at site 2 at the time of sample collection could have been different compared to if it had been collected at the same time as the other samples. Visual observations throughout the study period identified that the sediment composition at this site can change significantly and rapidly. Some sites were noticeably homogenous, such as site 1, so only one sample was taken. Others, such as site B, had only one sample taken because of the dominance of boulders and large gravel, and the scarcity of sand and smaller sized sediment. Site 3 presented difficulties with processing samples in the laboratory due to the inclusion of easily erodible limestone chips that had eroded from the backshore of the hapua. As a result, these samples were not sieved.

It is likely that the composition at each site varies over time, since after one flood there was a significant amount of fine sediment deposited along the shoreline, while after another larger flood the majority of the fine sediment was scoured from the bed of the lagoon. Therefore, the results from this study are specific to the time of sampling. Sediment composition will vary depending on the influence of fluvial and marine processes at the time.

4.6 Summary

This chapter outlined the various methods for measuring fine suspended sediment, fine sediment deposition, and sediment composition. The methods that were employed in this study were identified.

It is clear that suspended sediment, sediment deposition, and sediment composition are related to each other and are all affected by both fluvial and coastal processes in this hapua. These all vary spatially throughout this hapua and in different energy conditions. Floods have the greatest impact on sediment processes. The shape of the hapua also has a significant influence on the concentration of suspended sediment. The greatest concentration of suspended sediment was during flood conditions at sites that were close to the main flow of the river. It appears that the tide has no influence on suspended sediment.

Sediment deposition and composition vary throughout this hapua. Despite the limitations, it is evident that sediment composition varies throughout this hapua, and varies along the fringes with distance away from the waterline. It is also evident that sediment composition and deposition can vary over short time scales depending on the influence of fluvial and coastal processes.

In terms of managing sediment processes in coastal lagoons in New Zealand, there are currently no specific guidelines. Sediment processes in hapua are dynamic and can change rapidly. This has implication for both biota and the accumulation of metals and contaminants. The dynamic nature of the hapua must be taken into account if sediment processes in this type of system are to be monitored.

Chapter 5: Short-term baseline water temperature, conductivity, dissolved oxygen and pH

5.1 Introduction

Water quality parameters such as temperature, dissolved oxygen, conductivity and pH typically vary throughout coastal lagoons depending on fluvial and marine influences, lagoon circulation, and the water residence time (Kjerfve, 1994). Other factors such as ground-water discharge can also influence lagoon hydrology. These differences can result in distinct 'zones' throughout coastal lagoons (Herrera, 1994). Water quality parameters such as salinity and conductivity can be useful for establishing areas that are dominated by fluvial or seawater inputs (Marcovecchio *et al.,* 2006). Since water quality parameters have a direct influence on biota, these zones must be established so that the impacts of any change in the physical conditions to be determined. Knowledge of the spatial and temporal trends can give valuable information on the dynamics of lagoon systems (Marcovecchio *et al.,* 2006). Since lagoons vary significantly in terms of morphology and the influence of tides and fluvial processes, the hydrological regime of one lagoon cannot be assumed to be similar or the same as the hydrological regime of another. Water quality parameters such as temperature and salinity can also have a control over the geomorphological evolution in coastal lagoons as they can influence sedimentation and the growth of vegetation (Bird, 1994).

This chapter presents the results of water quality parameters in different areas of the Hurunui hapua under different fluvial and coastal energy conditions, and at different stages of the tide. The data in this chapter was collected at the same time and in the same places as the suspended sediment water samples discussed in Chapter 4 (refer to Figure 2.7 in Chapter 2).

This chapter is divided into four sections. Section 5.2 outlines the measured parameters, section 5.3 describes the methods used, section 5.4 details the results, section 5.5 contains the interpretation and discussion of results, and section 5.6 is a summary. An integrated discussion of the results and current water quality of this hapua is reserved for Chapter 9 after the presentation of nutrient results in Chapter 6, and short-term and long-term changes in the hapua behaviour and geomorphology in Chapter 7.

This chapter addresses the following research objective:

- To examine water quality parameters in different areas of the hapua and under different energy conditions.

5.2 Temperature, conductivity, dissolved oxygen, and pH as indicators for waterway health

In this study, temperature, conductivity, dissolved oxygen, and pH were measured. A number of water quality parameters were measured for a number of reasons. Firstly, more than one is required to give a reliable representation of waterway health, and for effective management practices to be put in place (Marcovecchio *et al.,* 2006). These parameters were also chosen as they are commonly used as indicators of waterway health in both rivers and coastal lagoons (Clapcott *et al.,* 2011; Ongley, 1996). Lastly, all of these parameters were chosen due to the influence they have on aquatic biota. If any of the parameters fall outside of the tolerance range, biota are adversely impacted (Environment Canterbury, 2009).

Surface water temperature can often vary throughout coastal lagoons and estuaries due to the influence of tides or other factors such as groundwater inputs (Alvarez-Borrego & Alvarez-Borrego, 1982; Herrera, 1994; Pereira *et al.,* 2009). Water temperature can also vary along a river due to: groundwater and surface water inputs, air temperature, shading by vegetation, cloudiness, river flow, and the shape of the river channel (Environment Canterbury, 2009). The intrusion of saline water from the ocean has a direct influence on water quality, sedimentation, the dispersal of pollutants, and biota (Prandle, 2011). One of the unique characteristics of hapua is the absence of a tidal prism. The only salt water that does enter does so via waves washing over the barrier or by sea spray. Hapua can have backwater effects as a result of the tide, but seawater does not enter the hapua. Overall guidelines for temperature in New Zealand rivers have not been developed since temperature varies both along a river and between rivers. However, the Australian and New

Zealand Environment and Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand (ANZECC & ARMCANZ) (2000) does recommend that river temperatures do not fall out of the 20^{th} and 80^{th} percentiles of a given river or site.

Conductivity is a measure of the ability of water to carry an electrical current and is commonly expressed as uS/cm (Chapman, 1996). Water is able to conduct a current due to the presence of dissolved ions, so the greater the concentration of dissolved ions, the greater the conductivity (Chapman, 1996; Dodds, 2002). Conductivity is an indirect measurement of the concentration of these ions, and due to its comparability (Figure 5.1) is sometimes used as a proxy for salinity (Hayward *et al.,* 2003). Salinity is the mass of the dissolved salts per unit volume. Because of the difficulties with measuring this, conductivity is often used instead (Dodds, 2002). The main ions that are found in seawater are sodium and chloride, but there are many other dissolved ions and solids apart from these that allow water to conduct an electric current (Chapman, 1996). Conductivity depends on naturally occurring minerals and on human activities that release contaminants to the waterway (Environment Canterbury, 2009). Like temperature, there are currently no guidelines for conductivity in New Zealand rivers or hapua systems. Freshwater typically has a conductivity ranging from 10 to 1000 uS/cm, and seawater 50 000uS/cm (Ongley, 1996). Conductivity in rivers in the Canterbury Region is typically between 50-250 uS/cm (Hayward *et al.,* 2003).

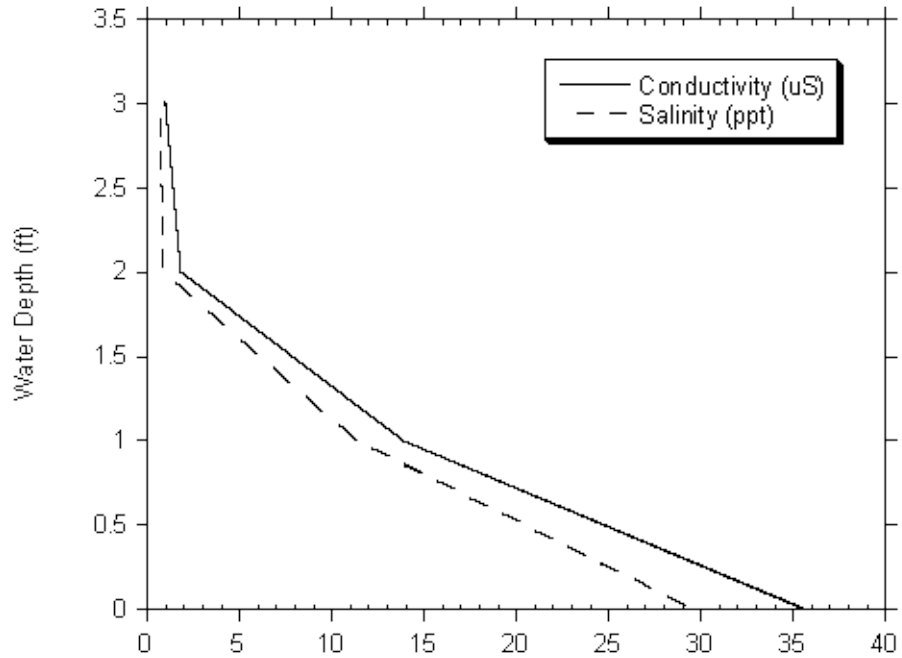


Figure 5.1: Relationship between conductivity and salinity in Moran Lake, a coastal lagoon in Santa Cruz County (John Gilchrist and Associates & Fall Creek Engineering, 2005).

Dissolved oxygen is a measure of the amount of oxygen gas that is dissolved in the water, and hence the oxygen availability for organisms. Organisms are adversely affected if the dissolved oxygen concentration falls below a certain level (Parlimentary Comissioner for the Environment, 2012). Dissolved oxygen can vary in response to water temperature and salinity (Environment Canterbury, 2009). It is measured in milligrams per litre (mg/L), and unpolluted water usually has a concentration no higher than 10 mg/L, with a lower limit guideline of 6 mg/L used in New Zealand (ANZECC & ARMCANZ, 2000; Ongley, 1996).

The pH of a water body is a measure of the acidity or basicity of the water and is important because it has a direct influence on both chemical and biological processes (Chapman, 1996). Water pH can be influenced by the concentration of dissolved acids such as fulvic acid, carbon dioxide, carbonate and bicarbonate ions, and algae respiration and photosynthesis (Chapman, 1996). pH is also influenced by: geology, runoff from agricultural areas, acid deposition, acid mine drainage, and acid sulphate soils (ANZECC & ARMCANZ, 2000; Bookter *et al.,* 2009). Seawater has a pH of around 8.2, and freshwater ranges from 6.5 to 8.0. The ANZECC guideline values for pH is 6.5 to 9.0 (ANZECC & ARMCANZ, 2000), although more specific values have been developed for upland and lowland rivers in New Zealand. The guideline values for pH in lowland rivers is 7.2 to 7.8, and for upland rivers 7.3

to 8.0 (Davies-Colley, 2000, p.5). Lowland sites are regarded as those that are less than 150 m in elevation, and upland sites those greater than 150 m in elevation (Davies-Colley, 2000). Alternatively, a common and more appropriate approach for guideline values is to use the 95th percentile for each monitoring site on each river. This approach allows for each site to have a specific guideline. The mean pH for the SH1 site on the Hurunui River based on year round data from 2005 to 2008 was 8.1, and the 75th percentile (7.5 to 8.8) is used to assess compliance with the guidelines at this site (Ausseil, 2010).

5.3 Methods

5.3.1 Principles and practices

Water quality parameter measurements can be taken *in-situ* with deployed equipment, or by taking spot measurements. While some parameters can be measured in the lab from water samples, most are taken *in-situ.* Water temperature, conductivity, dissolved oxygen and pH are typically measured *in-situ* since these can change if there is a change in temperature and sunlight (Lucena *et al.,* 2002). Some equipment such as a conductivity meter can take only a few parameters, whereas some such as the *Manta2 water quality multiprobe* can measure more.

Water temperature (°C) can be measured using a variety of *in-situ* multi-parameter instruments such as conductivity meters and dissolved oxygen probes (Lucena *et al.,* 2002). As well as the use of *in-situ* instruments, surface water temperature can also be measured using cameras equipped with thermal infrared imaging systems that is gaining attention. This method is particularly useful for showing spatial trends in surface water temperature, as well as detecting groundwater and tributary inputs (Faux *et al.,* 2001; Torgersen *et al.,* 2001), especially when *in-situ* measurements cannot be taken. The measurement of surface water temperature with a thermal camera is particularly useful in this environment since the mouth of the hapua often cannot be accessed due to safety concerns. Darker areas in the captured image correspond to cooler surface water temperature, and whiter areas to warmer surface water temperature.

Conductivity measurements are usually taken with a conductivity meter or a multi-parameter probe. Although conductivity can be attributed to dissolved ions other than sodium and chloride, it was deemed sufficient to measure conductivity in this study.

Dissolved oxygen can be measured with a variety of field meters, or alternatively, samples can be taken for analysis via the Winkler method that involves titration in the laboratory (Ongley, 1996; Pereira *et al.,* 2009).

pH is typically measured *in-situ,* but can also be measured in the laboratory via titration, although this method can be biased if the sample is not processed soon after collection (Chapman, 1996; Lucena *et al.,* 2002). Indicator dyes can also be used to give a rough estimate of pH (Chapman, 1996).

5.3.2 Sample collection

Water temperature, conductivity, dissolved oxygen, and pH were measured when suspended sediment samples were taken (refer to Figure 4.1 in Chapter 4). In the first low energy event, the outlet was at the northern end of the hapua, the outlet was oriented slightly southwards, and there was a small ponded area. The backshore and outlet sites were labelled B1 and O1 respectively. In the second low energy event the outlet was at the southern end of the hapua and the majority of the hapua was ponded and isolated from the main flow of the river. The backshore and outlet sites were labelled B2 and O2 respectively.

During the first flood the outlet was at the northern end of the hapua, and no ponded areas were present. The backshore and outlet sites were labelled B3 and O3 respectively. During the second flood the outlet was at the southern end and the majority of the hapua was isolated from the main current of the river. The backshore and outlet sites were labelled B4 and O4 respectively.

During the storm, the outlet was located at the southern end and was orientated to the north, and the majority of the hapua was ponded and isolated from the main current of the river. The backshore and outlet sites were labelled B5 and O5 respectively.

This study used the multi-parameter *Manta2 water quality multiprobe* manufactured by Eureka Environmental Engineering. This measured temperature, dissolved oxygen, conductivity, and pH in the field (Figure 5.2). Three measurements were taken at knee depth at the same time as the water samples collected for suspended sediment and nutrient concentration analysis. During the suspended sediment water sample collection, each replicate was taken 2 minutes apart per sampling event at each site. During collection of the nutrient samples, the average values from the *Manta2* were recorded after approximately 5 minutes.

An *Odyssey Depth and Temperature Logger* manufactured by Dataflow Systems Pty Limited was installed along the backshore halfway along the hapua (Figure 5.3) to measure the water level in the lagoon as well as the water temperature (°C) at hourly intervals. This was to allow for any unexpected change in water level to be recorded, as well as for the frequency of these events to be noted. Although short-term changes in the water level were recorded by the time lapse camera, the recorder allowed for the change to be measured quantitatively. This also allowed for changes in water level to be noted during the dark, which the time lapse cameras did not.

Figure 5.2: The multi-parameter probe *Manta2 water quality multiprobe* that was used for measuring water temperature, pH, conductivity and dissolved oxygen.

Figure 5.3: Water level recorder along the backshore of the Hurunui River hapua.

Although hapua do not have a tidal prism, thermal imagery was used to see whether there was a change in surface water temperature at the outlet in response to the tide related backwater effects, or if there was any spatial variation in water temperature which could indicate groundwater inputs. Thermal imagery was collected in the 8-14 μm waveband with a *PathFindIR forward-looking infrared system* (FLIR) to show surface water temperature near the outlet of the hapua. This covered a 36° h x 27° v field of view with an image size of 320 x 240 pixels. Images were taken at different locations along the cliff depending on where the outlet was. Because the reflectivity of thermal radiation from a water surface can be affected by clouds, the roughness of the water surface, and the angle at which the image is taken from (Torgersen *et al.,* 2001), the images were taken during the night when there were no clouds or wind.

5.3.3 Data analysis

The pH, conductivity, dissolved oxygen, and temperature values were downloaded from the manta into *Microsoft Excel* for analysis. The data was analysed to assess trends in the mean values between the sites, and at different stages of the tide. The data was also analysed to see whether there was a difference in the parameters in different energy conditions. *SPSS* was used to do post hoc statistical analyses.

While the thermal camera can take a video sequence over a number of hours, one still shot was taken from the start of either high or low tide, and then another was taken two hours later. Observations were made from these still images to see if there was any change in water temperature close to the outlet of the hapua.

5.3.4 Limitations and errors

There were several limitations with the measurement of water parameters in this study. Firstly, the results represent the conditions over the winter and spring. It is likely that the water parameters seasonally vary in this hapua.

Secondly, due to the time taken to reach each site, measurements were not taken at exactly high, mid, and low tide at each of the sites. Therefore, the results represent the approximate values at the different stages of the tide.

As with the nutrient and suspended sediment samples, measurements were not taken at the outlet during the high energy events due to safety concerns. If this had been possible, valuable extra information with regard to water parameters would have been obtained from the outlet. The depth and flow of the river also did not allow for samples to be taken across the width of the water body.

Due to malfunctioning equipment, the water level in the lagoon was not recorded. After the installation of the water level recorder, the river breached the barrier at the southern end of the hapua. As a result, the main part of the lagoon drained, the water level fell, and the recorder was no longer under water. The recorder was not reinstalled due to the concerns of the lagoon level rising again which could have made retrieval of the recorder difficult or even impossible.

While this study identified distinct zones in water quality parameters, the amount of time that the zones persist for is unknown. Further investigation is needed to determine this.

There are limitations with using a thermal camera to measure surface water temperature and this include: vertical thermal stratification throughout the water column if the flow is insufficient to ensure vertical mixing, thermal boundary effects at the water surface, and the reflectance of longwave radiation from the surrounding environment (Figure 5.4) (Torgersen *et al.,* 2001). The camera also cannot differentiate between emitted radiation and reflected radiation, so the image represents both reflected and emitted radiation. Thermal cameras also do not measure kinetic water temperature, instead measuring radiant water temperature. Therefore, it is assumed that the water column is sufficiently mixed so that there is minimal vertical stratification of water temperature (Torgersen *et al.,* 2001).

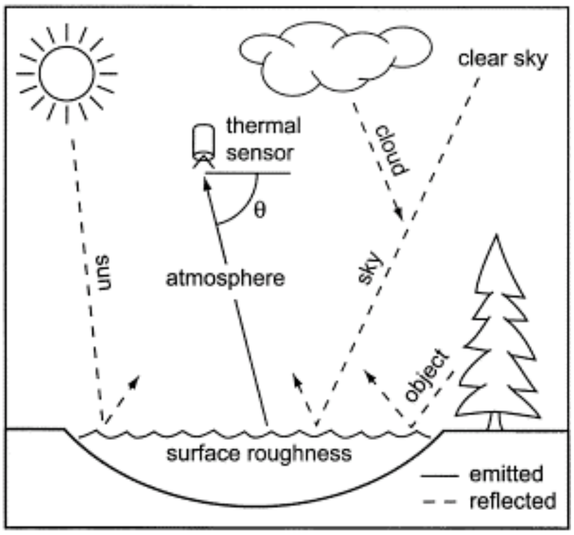


Figure 5.4: Sources of emitted and reflected radiation in streams and rivers (Torgersen *et al.,* 2001, p. 388).

As well as the limitations associated with using the thermal camera to detect surface water changes, there were a number of difficulties associated with using this method at this study site. The outlet of the hapua migrated significantly north during the period of this study. For the images from the camera to be of use, they had to be taken from a height. The cliff top at the end of the road, midway along the hapua was ideal, as well as a knoll about 200 m further north of the road end. As these were the only two locations ideal to use, observations were harder to make as the outlet migrated further northward away from these points.

The camera had to be used on a cloudless and windless night, and either high or low tide had to occur during the dark at a time when it was suitable to use the camera. Because of these difficulties, the number of times that the camera could be used was limited.

The error in the images could have been reduced if the images were taken from directly above the water. However, since the images were not processed using GIS, and only visual observations were made, this was of little concern.

The use of the thermal camera to detect surface water at different stages of the tide was deemed an unsatisfactory method because of the contradictory results. While thermal imagery can be useful for showing reach changes in water temperature (Faux *et al.,* 2001; Torgersen *et al.,* 2001), the use of this method at this site would need to be refined, and sources of error eliminated first in order to adequately analyse the influence of the tide on spatial patterns in the surface water temperature. Additional images would need to be taken with an airborne thermal camera to adequately identify and understand the spatial differences in surface water temperature at the Hurunui River hapua.

5.4 Results

5.4.1 Water temperature

Mean water temperature was similar in the low energy events and the storm event. Temperature ranged from 6.3°C at site B in the first flood to 12.5°C at site 2 in the second low energy event and at site 1 during the storm. Mean water temperature was the lowest during the flood conditions. In the low energy events and one of the floods there was little spatial variation. There was spatial variation in water temperature during the second flood and storm when the outlet was at the southern end of the hapua.

5.4.1.1 Low energy conditions

Mean water temperature varied between the sites in low energy conditions ($P<0.05$), despite a difference in the shape of the hapua and the location of the outlet (Figure 5.5). In the first low energy event there was a slight downward trend in temperature with distance downstream, and the mean temperature ranged from 10.3°C at site B1 to 11.3°C at site 2. A Least Significant Difference (LSD) test showed that site 1, 2, and 3 had the same mean, and sites B1 and O1 had the same mean.

In the second low energy event, mean temperatures were higher at all of the sites compared to the first event, and ranged from 11.6°C at site B2 to 12.5°C at site 2 (Figure 5.5). Site 1 had the same mean as sites 2, 3, and O2. Site 2 had a different mean to all of the sites excluding site 1. Site 3 was similar to all of the sites except for site 2. Site B2 had the same mean as sites 3 and O2. And site O2 had the same mean as all of the sites except for site 2.

Results from the *in-situ* measurements showed that all of the sites in the first low energy event had an increase in temperature from high to low tide (Figure 5.5). The peak mean water temperature at sites 1 and 2 occurred at mid tide. In the second low energy event, sites 1, 2, and O2 had an increase in temperature from high to low tide. Alternatively, sites 3 and B2 had a decrease, and the peak temperature occurred at mid tide for sites 1, 2, and O2.

The thermal camera results were variable. For two of the events, there was no change in the surface water temperature in the vicinity of the outlet at different stages of the tide (Figures 5.6 and 5.7). In these two events there was a difference in the area of warmer water over the two hours, but this occurred away from the outlet. Alternatively, on the 1st of June 2012, there was an increase in surface water temperature near the outlet towards high tide (Figure 5.8).

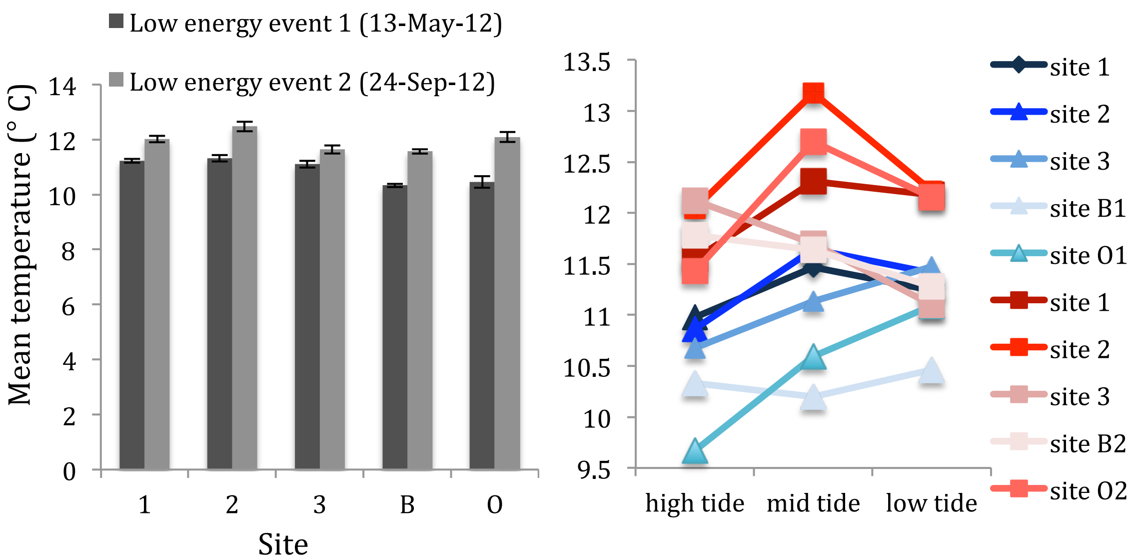


Figure 5.5: Mean temperature (°C) at each site in two low energy events with error bars (left). Mean water temperature at each site at different stages of a tidal cycle in low energy event 1 (blue), and low energy event 2 (red) (right).

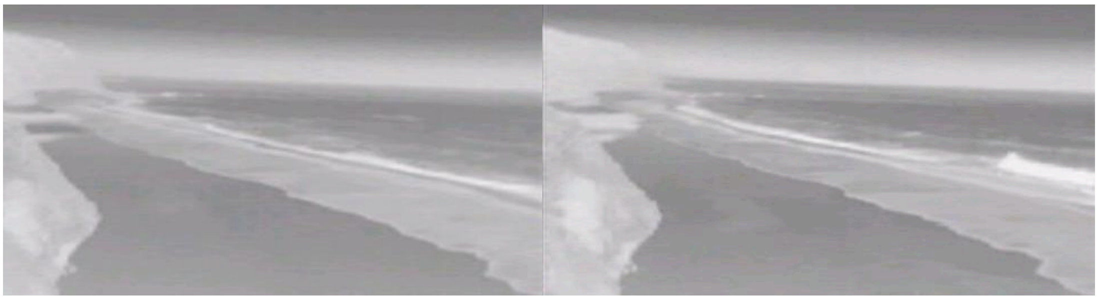


Figure 5.6: Thermal camera imagery looking towards the outlet of the hapua one hour before low tide (left), and one hour after low tide (right) on the 1st of June 2012.

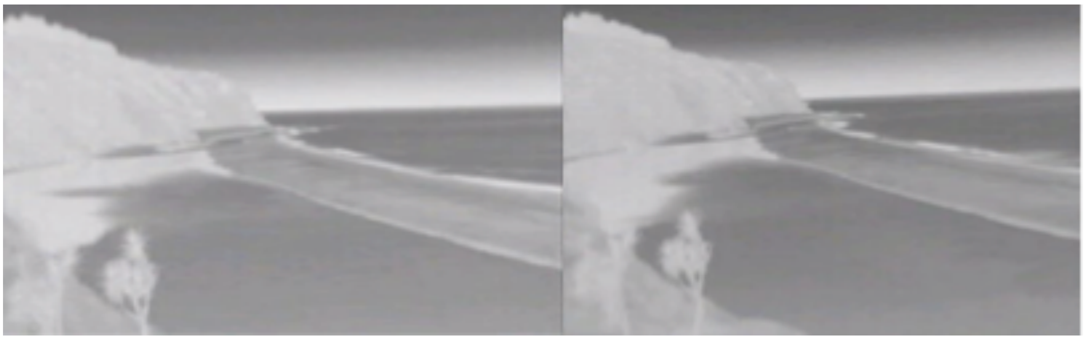


Figure 5.7: Thermal camera imagery looking towards the outlet of the hapua at high tide (left), and two hours after high tide (right) on the 21st of June 2012.

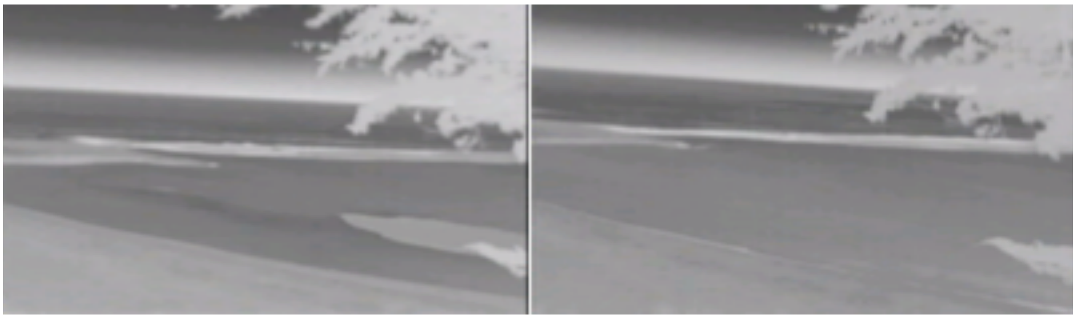


Figure 5.8: Thermal camera imagery of the outlet two hours before high tide (left), and at high tide (right) on the 22nd of September 2012.

5.4.1.2 Flood conditions

The mean water temperature decreased slightly with distance downstream during the first flood (Figure 5.9). The highest mean temperature of 6.6°C was observed at site 1, and the lowest of 6.3°C at site B3. Although there was a decrease in temperature downstream, the difference between the most upstream and the most downstream site was only 0.3°C. In the second flood, mean water temperature between the sites varied. Sites 1 and 2 had a lower mean temperature of around 8°C, and sites 3 and B4 were about a degree higher in temperature.

Analysis of variance showed that there was no difference in the mean water temperature between the sites in the first flood (P>0.05). In the second flood there was a difference in the mean water temperature between the sites (P<0.05). A LSD test showed that sites 1 and 2 were similar in mean water temperature, and sites 3 and B4 were similar.

There was an increase in mean temperature at all of the sites from high to low tide during the first flood (Figure 5.9). There was an increase of approximately 0.7°C at each site from high to low tide. In the second flood, there was also an increase in mean temperature from high to low tide. Sites 1 and 2 had a smaller increase (approximately 0.3°C) than the increase at sites 3 and B4 (approximately 0.7°C).

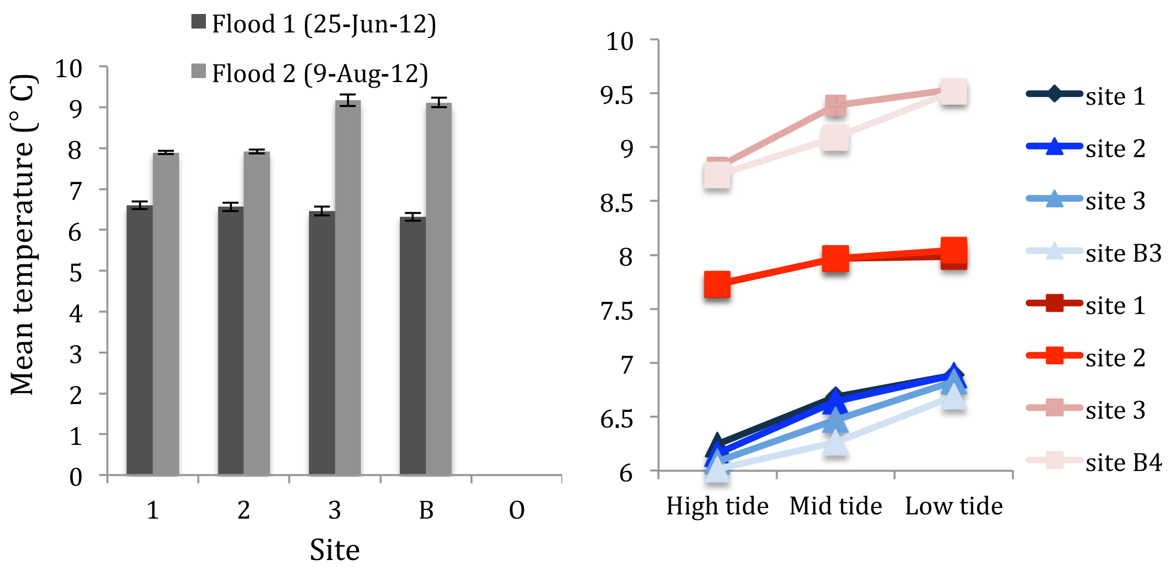


Figure 5.9: Mean water temperature (°C) at each site during two flood events with error bars (left). Mean water temperature at each site at different stages of a tidal cycle during flood 1 (blue) and flood 2 (red) (right).

5.4.1.3 Storm conditions

Mean water temperature during a storm was highest at sites 1 and O5 (Figure 5.10). The temperature at these sites was around 12.5°C. Sites 2, 3, and B5 were similar in temperature and were 11.3°C. There was spatial variation in mean temperature between the sites

(P<0.05). A LSD test showed that sites 1 and O5 had a similar mean water temperature, and site 3 was similar to both sites 2 and B5.

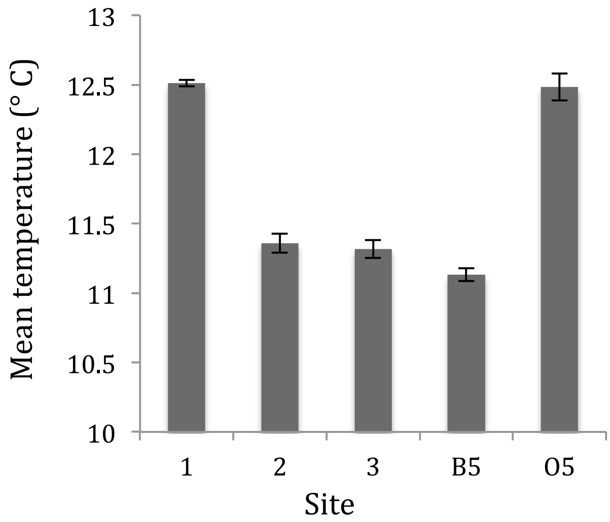


Figure 5.10: Mean water temperature (°C) at each site during a storm on the 7th of November 2012 with error bars.

5.4.2 Conductivity

Conductivity throughout the hapua depended on the shape of the hapua. Areas that were ponded and away from the main current of the river had higher conductivity concentration. There was a large amount of variation in the conductivity concentration between the events, in the first low energy event the values were around 100 uS/cm, and in the storm the values were around 12, 000 uS/cm.

5.4.2.1 Low energy conditions

During the first low energy event, mean conductivity concentration ranged from 98.2 uS/cm to 109.1 uS/cm, and varied between the sites (P<0.05) (Figure 5.11). A LSD test showed that all of the sites had a similar mean conductivity concentration except for site B1. The mean conductivity concentration was around 100 uS/cm at all of the sites. During the second low energy event mean conductivity concentration ranged from 94.7 uS/cm at site 1 to 856 uS/cm at site B2, and there was spatial variation between the sites (P<0.05). A LSD test showed that sites 1, 2, and O2 had similar mean conductivity concentration and sites 3 and B2 had a similar mean conductivity concentration. Sites 1,2 and O2 had a similar mean conductivity concentration to the first event, however sites 3 and B2 were much higher. Site 3 had a conductivity of 495 uS/cm, and site B2 a conductivity of 856 uS/cm. These sites were isolated from the main current of the river.

In the first low energy event, mean conductivity concentration increased from high to low tide at all of the sites except for site B1 which experienced a decline (Figure 5.12). In the second low energy event, sites 2, 3, and O2 had an increase in mean conductivity concentration from high to low tide, and sites 1 and B2 had a decrease.

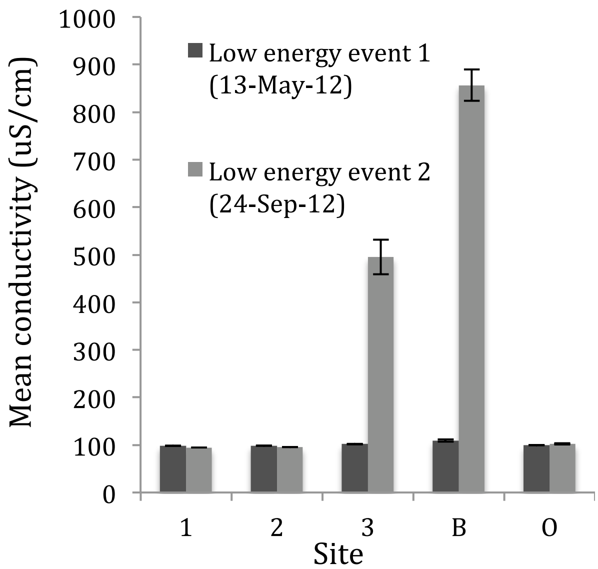


Figure 5.11: Mean conductivity (uS/cm) at each site in two low energy events with error bars.

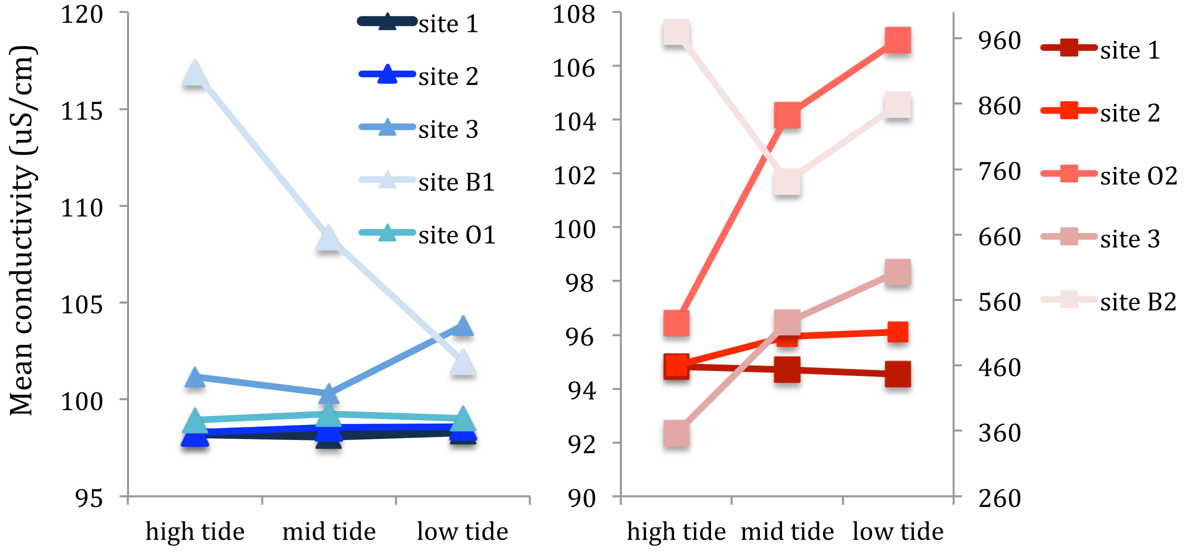


Figure 5.12: Mean conductivity (uS/cm) at each site at different stages of a tidal cycle in low energy event 1 (left) and low energy event 2 with site B2 on the secondary axis (right).

5.4.2.2 Flood conditions

Mean conductivity concentration ranged from 73.2-73.6 uS/cm in the first flood and did not vary between the sites ($P>0.05$) (Figure 5.13). Site 3 had the lowest mean conductivity concentration. In the second flood there was a significant difference in mean conductivity concentration between the sites ($P<0.05$). The mean conductivity concentration at sites 3 and B4 was greater than 17000 uS/cm and a LSD test showed that the conductivity at sites 1 and 2 was the same, and the conductivity at sites 3 and B4 was the same. Mean conductivity concentration at sites 1 and 2 were slightly higher than the values observed at these sites in the first flood.

Mean conductivity concentration increased at all of the sites from high to low tide in the first flood, although the increase was minimal (Figure 5.14). During the second flood, there was an increase from high to low tide at sites 1 and 3, and a decrease at sites 2 and B4. The increase at site 3 was much larger than the difference at the other sites.

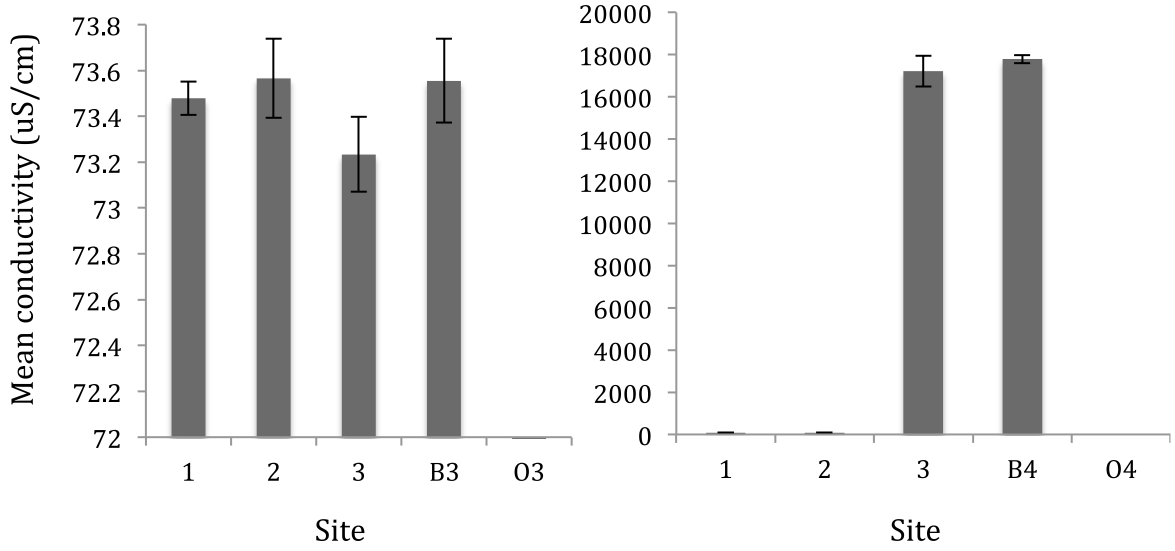


Figure 5.13: Mean conductivity (uS/cam) at each site during flood 1 on the 25th of June 2012 with error bars (left). Mean conductivity at each site during flood 2 on the 9th of August 2012 with error bars (right). Note the different scale on the two graphs.

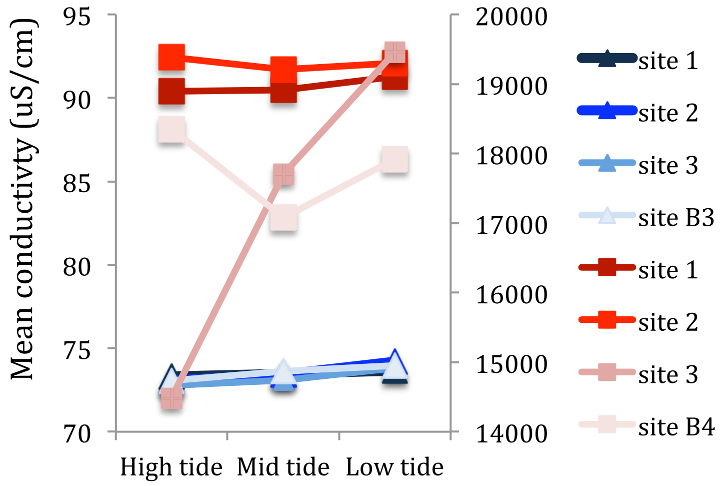


Figure 5.14: Mean conductivity (uS/cm) at each site at difference stages of a tidal cycle during the first flood (blue) and second flood (red).

5.4.2.3 Storm conditions

Mean conductivity concentration in the storm ranged from 93 uS/cm at site 2 to 12377 uS/cm at site O5 (Figure 5.15). Mean conductivity concentration varied between the sites (P<0.05). Mean conductivity concentration ranged from 93 uS/cm at site 2, to 12377 uS/cm at site O5. Sites 1 and 2 had a much lower mean conductivity concentration compared to the other sites. A LSD test showed that the only sites that had the same mean was sites 1 and 2.

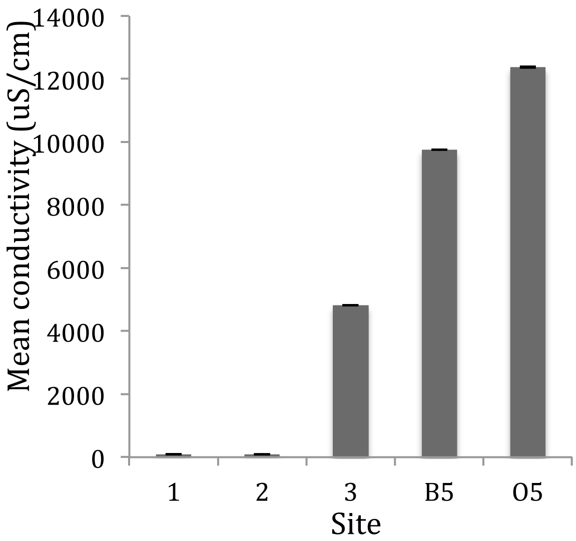


Figure 5.15: Mean conductivity (uS/cm) at each site during a storm on the 7th of November 2012 with error bars.

5.4.3 Dissolved oxygen

There was a minimal amount of spatial variation in dissolved oxygen in the low energy events and the floods. The greatest spatial variation was in the storm. Dissolved oxygen was highest in the floods.

5.4.3.1 Low energy conditions

Mean dissolved oxygen concentration ranged from 12.2 mg/L to 13.6 mg/L in the first low energy event, and from 9.1 mg/L to 10.8 mg/L in the second low energy event (Figure 5.16). There was minimal spatial variation in mean dissolved oxygen concentration in both of the low energy events ($P>0.05$). Mean dissolved oxygen concentration was greater at all of the sites during the first low energy event. Values were around 13 mg/L, and in the second event, around 10 mg/L.

During the first low energy event, there was a decrease in mean dissolved oxygen concentration at all of the sites from high to low tide (Figure 5.16). During the second low energy event, there was also a decrease from high to low tide at all of the sites except for site 1 which had an increase.

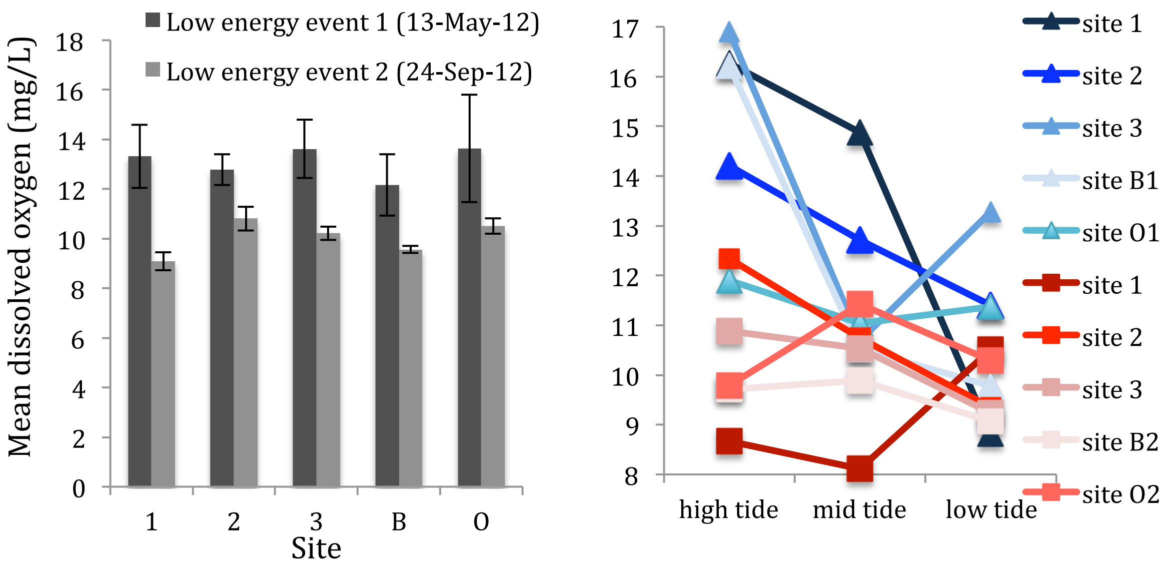


Figure 5.16: Mean dissolved oxygen (mg/L) at each site in two low energy events with error bars (left). Mean dissolved oxygen at each site at different stages of a tidal cycle in the first low energy event (blue), and the second low energy event (red) (right).

5.4.3.2 Flood conditions

Mean dissolved oxygen concentration ranged from 17.2 mg/L at site B3 to 18.5 mg/L at site 3 in the first flood (Figure 5.17). There was no spatial variation in mean dissolved oxygen concentration during the first flood (P>0.05). Mean dissolved oxygen concentration was lower during the second flood and ranged from 11.3-13.6 mg/L. There was spatial variation in mean dissolved oxygen concentration during the second flood (P<0.05). A LSD test showed that sites 1, 2 were the same, and sites 3 and B4 were the same.

All of the sites except for site B3 in the first flood had a decrease in mean dissolved oxygen concentration from high to low tide (Figure 5.17). During the second flood, all of the sites had a decrease in mean dissolved oxygen concentration except for site 2.

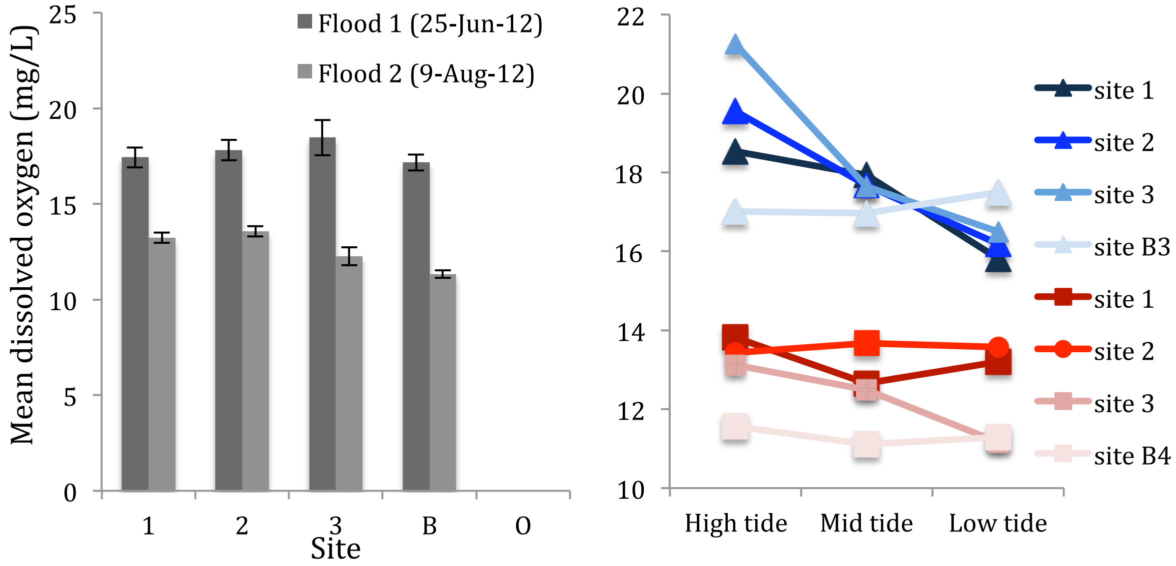


Figure 5.17: Mean dissolved oxygen (mg/L) at each site during two floods with error bars (left). Mean dissolved oxygen at each site at different stages of a tidal cycle during flood 1 (blue) and the flood 2 (red) (right).

5.4.3.3 Storm conditions

During storm conditions on the 7th of November 2012, mean dissolved oxygen concentration ranged from 8.6 mg/L at site 3 to 10.0 mg/L at site 1 (Figure 5.18). Mean dissolved oxygen concentration varied between the sites ($P<0.05$). A LSD test showed that sites 1, 2, and O5 had the same mean. Sites 3 and B5 mean the same mean dissolved oxygen concentration, and site B5 and O5 also had the same mean.

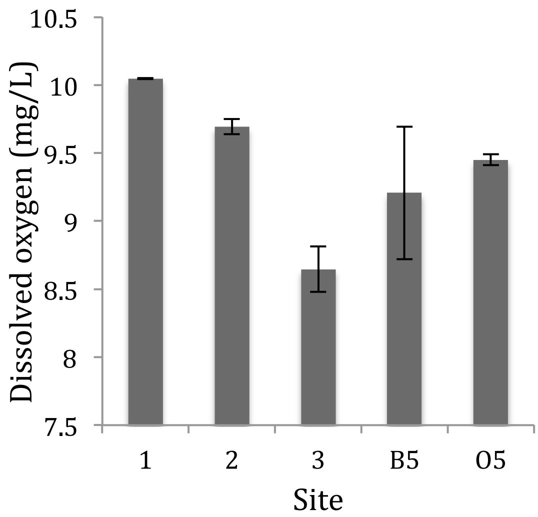


Figure 5.18: Mean dissolved oxygen (mg/L) at each site during a storm on the 7th of November 2012 with error bars.

5.4.4 pH

Mean pH varied throughout the hapua in all of the energy events. The greatest spatial variation was in the storm. All of the sites in all of the events were alkaline.

5.4.4.1 Low energy conditions

In the first low energy event there was a general downward trend in mean pH with distance downstream (Figure 5.19). Site B1 had the lowest mean pH of 7.8, and site 1 had the highest of 8.2. There was spatial variation in mean pH between the sites during the first low energy event ($P<0.05$). A LSD test showed that site B1 had the same mean pH as all of the sites except for sites 2 and O1. Except for site B1, mean pH was greater in the first low energy event. In the second low energy event there was a general upward trend in mean pH with distance downstream, with site 1 having the lowest pH of 7.8, and site B2 having the highest of 8.1. Site O in both events deviated from the downstream trend. There was also spatial variation in the second low energy event ($P<0.05$).

During the first low energy event, there was an increase at all of the sites from high to low tide except for site 1 (Figure 5.19). During the second event, there was an increase at all of the sites except for site B2.

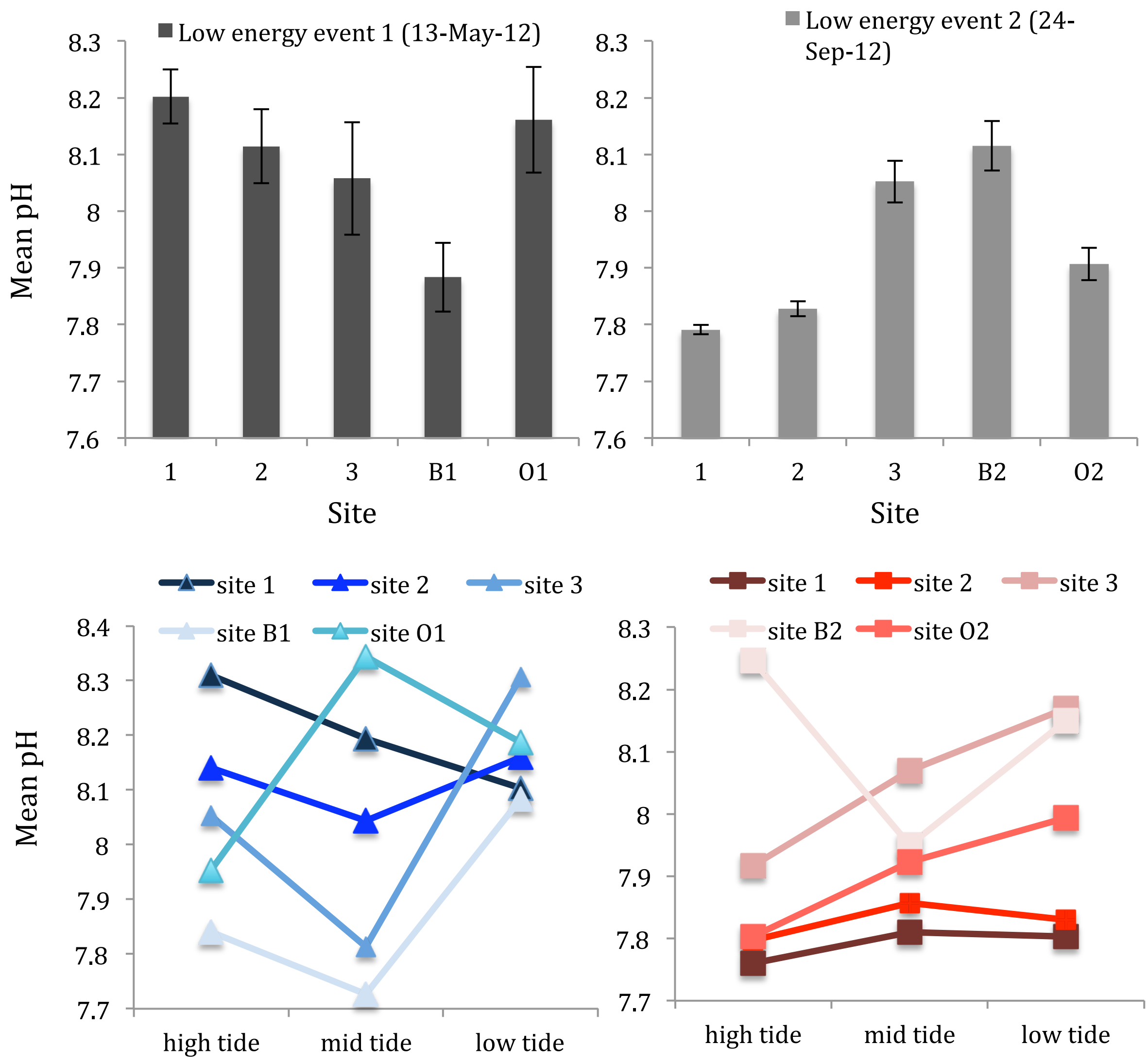


Figure 5.19: Mean pH at each site with error bars in low energy event 1 (top left), and in low energy event 2 with error bars (top right). Mean pH at each site at different stages of a tidal cycle in low energy event 1 (blue), and low energy event 2 (red) (right).

5.4.4.2 Flood conditions

In the first flood, mean pH increased with distance downstream, ranging from 7.6 at site 1 to a pH of 7.8 at site B3 (Figure 5.20). There was spatial variation in mean pH in both of the floods and the pH at all of the sites during both flood events was slightly alkaline ($P<0.05$). In the first flood, sites 1 and 2 were similar, and sites 3 and B3 were similar. In the second flood, the mean pH ranged from 7.7 at site 1 to 7.9 at site 3.

During the first flood, there was a decrease in mean pH at all of the sites from high to low tide (Figure 5.20). During the second flood event there was also a decrease at all of the sites except for site B4 which did not change.

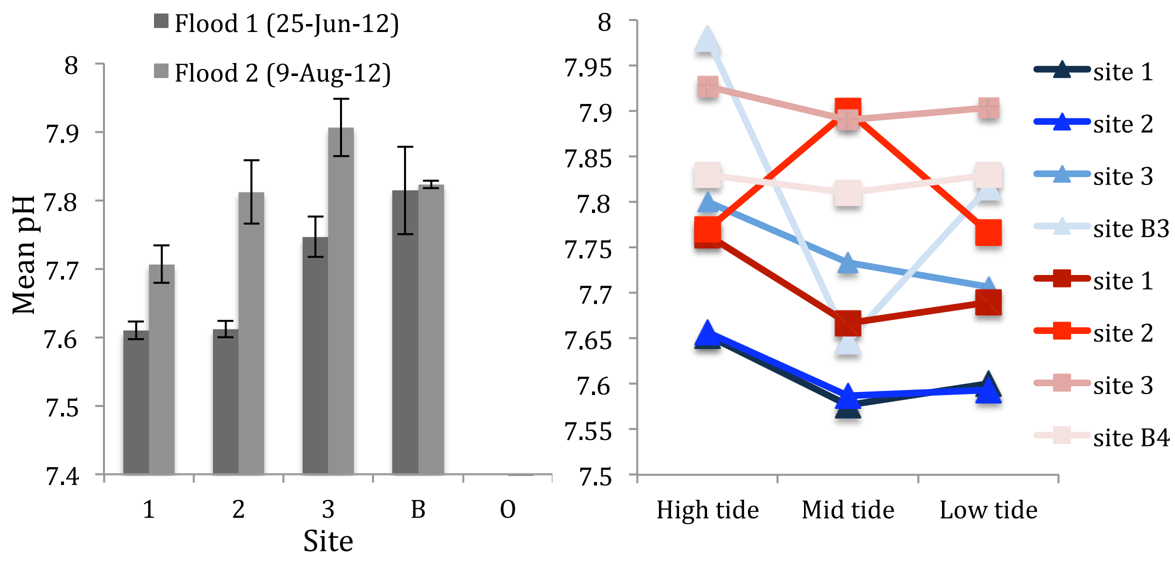


Figure 5.20: Mean pH at each site during two floods with error bars (left). Mean pH at each site at different stages of a tidal cycle during flood 1 (blue) and flood 2 (red) (right).

5.4.4.3 Storm conditions

During storm conditions on the 7th of November 2012, mean pH at sites 1 and 2 was 7.9 and 7.7 respectively, while the pH at the other sites was around 8.3 (Figure 5.21). There was spatial variation in pH ($P<0.05$). A LSD test showed that sites 3 and 5 were the only sites with a similar mean. Sites 1 and 2 had a much lower mean pH compared to sites 3, B5, and O5.

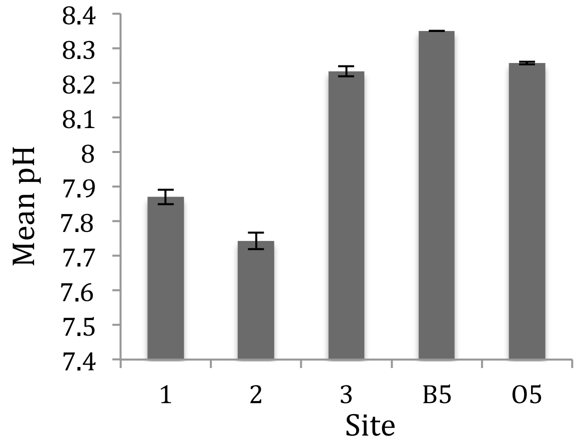


Figure 5.21: Mean pH at each site during a storm event on the 7th of November 2012 with error bars.

5.5 Interpretation and discussion

5.5.1 Water temperature

Water temperature varied between the sites in some of the events. During the low energy conditions, there was no spatial variation. There was also no spatial variation during the first flood and during the low energy events when the outlet was located at the northern end of the hapua. The similar flow of water past each site would have limited the spatial variation. Spatial differences in water temperature were present when the outlet was located at the southern end of the hapua during the second flood and during the storm. Spatial trends in water temperature at this hapua are most likely controlled by the location of the outlet and the shape of the hapua. For instance, during the second flood, the outlet was located at the southern end of the hapua and the majority of the hapua was ponded and away from the main current of the river. As a result, the ponded sites that were away from the main current of the river were warmer. The influence of the shape of the hapua and flow on the water temperature was also evident during the storm, although the opposite trend was observed. The ponded sites (2, 3, and B5) had a lower water temperature compared to the sites with greater flow (sites 1 and O5). The difference in the trend between the two events may have been due to the difference in river flow as the flow during the second flood was much higher compared to the river flow during the storm.

As well as the influence of river flow and the shape and location of the hapua outlet on spatial trends in water temperature throughout this hapua, it is likely that spatial trends also occur due to a variety of interacting factors such as shade, water depth, wind, and spring inputs (Gordon *et al.,* 2004; Herrera, 1994), although the relative influence of these factors is difficult to quantify. Therefore, it is concluded that spatial trends in water temperature in this hapua exist when the outlet is located at the southern end of the hapua, or when significant ponded areas are present that are isolated from the main flow of the river, especially during storm and flood conditions.

Water temperature varied between the different energy conditions. Temperature was the highest during the storm (11.1°C to 12.5°C) followed by the low energy events (10.3 to 12.5°C). The lowest water temperatures occurred during the floods. Water temperature in the first flood ranged from 6.3 to 6.6°C, and from 7.9 to 9.2°C in the second flood. The lower temperatures during the floods were likely due to the higher river flow. It is also likely that these lower temperatures were attributed to sampling occurring during the middle of winter. ANZECC (2000) recommends that river temperatures do not fall out of the 20th and 80th percentiles of the ecosystem reference data. Overall guidelines for New Zealand rivers have not been developed since temperatures can vary greatly both along a river and between rivers. The year round (data taken from 2005-2008) mean temperature at the monitoring site closest to the coast on the Hurunui River (State Highway 1) was 13.0 °C, and the 25th and 75th percentiles 9.2°C and 16.8°C respectively (Ausseil, 2010). The temperatures at this hapua were within the 25th and 75th percentiles during the low energy events, and below this range during the first flood that occurred in the middle of winter. Although the water temperature was outside of the 25th and 75th percentiles during the flood, it is likely that this was temporary, so is of minimal concern. While the mean temperature in the ocean close to the mouth is similar to the mean temperature in the lower river, there is less variation in water temperature. The average sea surface temperature at Gore Bay, just north of the Hurunui River mouth, from 1981 to 2005 was 13.3°C (Surf-Forecast, 2012). The sea temperature ranged from 11.7°C to 14.7°C during this period (Surf-Forecast, 2012). The water temperature in the hapua will depend on the residence time of any seawater that has entered in over topping events, surface heating, and mixing of the water column.

The water temperature in coastal lagoons is important as it has a direct influence on aquatic biota, especially primary producers (Bintz *et al.,* 2003; Gordon *et al.,* 2004). Primary producers such as macroalgae respond to elevated water temperatures by increasing photosynthesis. The rate of organic matter decomposition also increases with an increase in water temperature (Bintz *et al.,* 2003). Although temperature varied spatially in this lagoon during some of the sampling events, it is unknown if temperature is the primary factor controlling periphyton growth in this hapua. It is likely that salinity and the stability of the substrate have a major control on the presence of biota. The dynamic position of the outlet would result in an unstable substrate, especially for periphyton growth. Sites 3, B, and O experience a rise in salinity during storm conditions when waves overtop the barrier, therefore biota present at these sites would have a tolerance to saline conditions. If the temperature fluctuates or changes in relation to river flow or the morphology of the hapua, it is likely that the location of biota will change depending on their tolerance ranges (Gordon *et al.,* 2004). Since species respond to changes in temperature differently, there is the potential for community composition and balance to be affected (Bintz *et al.,* 2003; Short & Neckles, 1999) if there is a significant long-term change in water temperature throughout the hapua.

Tides can have an influence on water temperature in coastal lagoons (Lopes *et al.,* 2001). The *in-situ* measurements showed an upward trend in water temperature at most of the sites from high to low tide in the low energy and flood events. The only exception was sites 3 and B2 during the second low energy event where there was a decrease in temperature from high to low tide. During this event, the outlet was at the southern end of the hapua and sites 3 and B2 were ponded and away from the main current of the river. Although the shape of the hapua was similar during the second flood event, the water temperature did not decrease at sites 3 and B4 from high to low tide. Although the reason for the opposite trend at sites 3 and B4 during the second low energy event is unclear, it is concluded from these measurements that the water temperature typically increases in most areas of the hapua from high to low tide.

The results from the thermal camera were variable. In contrast to the *in-situ* measurements which showed a general upward trend in water temperature from high to low tide, the images taken on the 1st of June 2012 showed a greater area of warmer water closer to high tide. The images taken on the other occasions did not show a difference in surface water temperature at different stages of the tide. The absence of any difference on the 21st of June 2012 could have been due to the elongated outlet, which would have reduced the backwater effect near the outlet. The absence of any difference on the 22nd of September 2012 may have been due to the outlet being adjacent the main river channel. Because of the inconclusive and contradictory results from this method, the *in-situ* results are considered to be the most reliable.

It is likely that there are numerous reasons for the observed results at different stages of the tide. These factors could include the effect of the change in air temperature on the water temperature throughout the day and groundwater inputs (Herrera, 1994), and also shading by the cliff along the backshore of the hapua. The images from the thermal camera on the 21st of June and the 22nd of September 2012 showed a difference in surface water temperature over the two hours away from the outlet. This demonstrates that there are potentially other factors attributing to spatial differences in water temperature in this hapua. These could include the characteristics and morphology of the river bed as these can influence heat loss and gain from the water (Alvarez-Borrego & Alvarez-Borrego, 1982; Beschta *et al.,* 1987; Faux *et al.,* 2001). Shading along waterways can influence the surface water temperature (Beschta *et al.,* 1987), so differences in temperature due to shading along the backshore of the hapua during the day, and the differential loss of heat from the land along the backshore is plausible. The change in surface water temperature on the 21st of June 2012 may have been due to the influence of a small stream in the vicinity of the observed temperature change. Although stream inputs can alter surface water temperature, due to the size of the small streams entering the hapua, the influence on the surface water temperature in the hapua was likely to have been minimal (Beschta *et al.,* 1987). Thermal imagery can be useful in identifying groundwater inflows in streams (Faux *et al.,* 2001), so it is possible that the observed difference in surface water temperature at different stages of the tide could have been due to groundwater inputs. However, groundwater inputs are difficult to quantify (Smith, 1994), and without further analysis, this hypothesis cannot be supported.

5.5.2 Conductivity

Spatial differences in mean conductivity concentration in this hapua depend on the shape of the hapua and the location of the outlet. Some coastal lagoons have a salinity gradient that decreases with distance upstream from the outlet (Alvarez-Borrego & Alvarez-Borrego, 1982; Marcovecchio *et al.,* 2006), however this trend did not occur in this hapua. The deviation from this trend was not unexpected since hapua do not have a tidal prism (Hart, 1999). Salinity zones in some coastal lagoons also depend on freshwater inputs (Marcovecchio *et al.,* 2006). Instead of conductivity depending on the degree of tidal inflow or freshwater input, conductivity in this system is determined the extent of waves washing over the barrier during sea storms (Hart, 1999), and the shape of the hapua.

When the outlet was located at the northern end of the hapua, regardless of river flow, there was a minimal amount of variation in mean conductivity concentration between the sites. However when the outlet was located at the southern end of the hapua, and the majority of the hapua was ponded, significant spatial differences in mean conductivity concentration existed. Sites 3 and B5, which were ponded in the second low energy event, second flood, and during the storm, had much higher mean conductivity concentration compared to the other sites that were close to the main flow of the river. When the outlet was at the southern end of the hapua, seawater that had entered the lagoon during storms was flushed from the system much slower compared to sites 1 and 2, which were close to the main current of the river. As a result, the water residence time and conductivity is greater in ponded areas.

This same trend, where the salinity or conductivity in a coastal lagoon is dependent on the proximity to freshwater and seawater influences, has also been observed Óbidos Coastal Lagoon in Portugal (Pereira *et al.,* 2009). In this lagoon, inner branches that are more dominated by fluvial inputs have lower conductivity concentrations compared to areas that are closer to the outlet of the lagoon (Pereira *et al.,* 2009). Conductivity is also affected by water temperature; the higher the temperature the higher the conductivity (Ongley, 1996). In general, site B5 had a low temperature but high mean conductivity concentration. Since the expected relationship was not evident, the higher conductivity concentration is likely to be from the longer residence time of saltwater.

Despite being closest to the outlet, site O5 during the low flow conditions and flood events did not have a higher mean conductivity concentration compared to the other sites. During the first low energy event, influx of seawater through the outlet was observed, and because of this it was expected that this site would be higher in conductivity compared to the other sites. However, the mean conductivity concentration at this site was similar to the other sites. Conductivity in estuarine coastal lagoons can be influenced by the tides (Lopes *et al.,* 2001), but since the conductivity was similar to the other sites, and there was a minimal difference at different stages of the tidal cycle, it is concluded that the narrowing of the river and the greater flow at the outlet quickly flushes any seawater that had entered the lagoon through the outlet. The only time that conductivity will be greater at the outlet is during storm conditions when waves wash over the barrier.

Spatial variation in mean conductivity concentration can be indicated by the presence of algae species. Evidence for spatial differences in conductivity concentration in this hapua is also shown by the presence of algae species in ponded areas. The presence of the brackish species of algae *Enteromorpha* cf. *intestinalis* at site 4 suggests conductivity concentration is higher at this site.

Because of the spatial differences observed in this study, there are several conclusions with regard to the spatial variation in conductivity concentration in this hapua. Firstly, it is concluded that the greatest spatial variation occurs when ponded areas are present, especially when the outlet is located at the southern end of the hapua. Alternatively, if the outlet is located at the northern end of the hapua and there are no significant ponded areas, spatial variation in conductivity is minimal. Secondly, the highest conductivity concentration is areas that are ponded and isolated from the main current of the river.

Conductivity concentration in this hapua in the three energy conditions is dependent on the shape of the hapua. The highest values were in the flood event at the sites that were ponded. The residence time of seawater that had entered the hapua via overtopping of the barrier during sea storms would have been higher at these sites. This trend was also evident during the storm event. While conductivity at this hapua is influenced to an extent by the energy conditions, the main control is the shape of the hapua and the flow at each site. Conductivity in the Waipara River is related to river flow; the lower the flow, the higher the concentration of ions, and the greater the conductivity (Hayward *et al.,* 2003). This trend was evident at this site since areas with lower flows had higher conductivity concentration. Therefore, any change in river regime that alters the river-marine balance enough to affect the geomorphic dynamics could influence conductivity concentration in the lagoon.

ANZECC (2000) currently has no guidelines for conductivity for New Zealand rivers, and since hapua is not a river channel, the conductivity guidelines for rivers cannot be applied to these systems. Conductivity in freshwater can range from 10 to 1000 uS/cm (Chapman, 1996), although braided rivers in the Canterbury Region vary between 50-250 uS/cm (Hayward *et al.,* 2003), and seawater conductivity is usually around 51, 500 uS/cm (Suttar *et al.,* 1990). Regardless of the energy condition, conductivity in the unponded sites was at the lower end of the range for freshwater (10-1000 uS/cm) (Ongley, 1996), although were within the expected range for braided rivers in the Canterbury Region (50-250 uS/cm). The mean conductivity concentration at State Highway 1 (SH1) on the Hurunui River based on year round data from 2005-2008 is 88uS/cm, and the 25th and 75th percentiles 80uS/cm and 97 uS/cm respectively (Ausseil, 2010). The values for many of the sites in all of the energy conditions were not within the 25th and 75th percentiles for the SH1 site. This was likely due to the marine influence where waves overtopping the barrier caused conductivity to increase. Conductivity concentration in this hapua can be higher than the range for freshwater, particularly in ponded areas. Although the mean conductivity concentration in these areas was higher than the range for freshwater, it was considerably lower than the typical value for seawater. Therefore, the ponded areas represent neither fresh nor seawater, instead representing brackish water.

Conductivity can be a useful indicator of polluted areas (Ongley, 1996). The higher mean conductivity concentration, especially at sites 3 and B5 suggests that there is a greater concentration of dissolved ions and solids. In rivers, high conductivity values are usually associated with poor water quality or surface runoff (Ongley, 1996). The higher conductivity concentration at these sites is instead likely due to the longer residence time of seawater that has entered via overtopping of the barrier. During the first low energy event when the outlet was located at the northern end, conductivity concentration was outside of the recommended 25th and 75th percentiles. Since conductivity concentration was still within the freshwater range, the water is considered to be relatively healthy.

There was a general upward trend in mean conductivity concentration from high to low tide at all of the sites in the low energy events and flood events. The exception to this was site 1 in the second low energy event when the outlet was located at the southern end of the hapua, site 2 during the second flood event when the outlet was also located at the southern end, and site B5 in the two low energy events and the second flood. If the tide did influence conductivity, it is expected that there would be an decrease from high to low tide. The results suggest that the influence of the tide on conductivity concentration is the greatest at site B5. The increase at the other sites for most of the time suggests that the tide has a limited influence on conductivity concentration.

When examining spatial and temporal trends in conductivity concentration it is important that seasonal changes are considered. A considerable difference was observed in conductivity between spring and summer in the two basins in the Tancada coastal lagoon basins in the Ebro River Delta (Comin *et al.,* 1991). It is possible that conductivity in this system also varies according to the season in relation to the seasonal differences in river flow and sea storms.

5.5.3 Dissolved oxygen

There was a minimal amount of spatial variation in dissolved oxygen concentration in the low energy and flood events. Variation was greater during the storm. The minimal variation in the low energy and flood events was unexpected since there was spatial variation in temperature and conductivity. Since the solubility of oxygen in water decreases with an increase in temperature (Ongley, 1996), it was expected that the warmer sites would have had the lowest dissolved oxygen concentrations. However, this trend did not occur in the two low energy events, the first flood event, and the storm, so it is likely that dissolved oxygen concentration at these sites is significantly affected by salinity rather than temperature. The expected relationship between temperature and dissolved oxygen concentration during the second flood event was present. The warmer sites 3 and B4 had a lower concentration of dissolved oxygen compared to the colder sites 1 and 2. During this event the outlet was at the southern end of the hapua and sites 3 and B4 were isolated from the main current of the river. This demonstrates that the morphology of the lagoon and the presence of ponded areas can have an influence on dissolved oxygen concentration within this system. The unexpected minimal variation in mean dissolved oxygen concentrations at the different sites, especially during the low energy events and floods, was likely due to other interacting factors which can affect dissolved oxygen such as: photosynthesis and respiration of aquatic primary producers, water temperature, solar radiation, wind, and salinity (Hayward *et al.,* 2003; Hull *et al.,* 2008).

Dissolved oxygen is often used as an indicator of waterway health (Ongley, 1996). Unpolluted waters usually have a dissolved oxygen concentration around 10 mg/L or less, but during the first low energy event and the floods the concentration was above 10 mg/L. This suggests that the waterway was not entirely pristine during these events, but since the concentration was not particularly higher than 10 mg/L, and the values in the other sampled events was at or below 10 mg/L, the current health of the waterway is not of particular concern (Ongley, 1996). The values for dissolved oxygen concentration at the Hurunui hapua were also not particularly higher than the typical values that have been recorded in the river at SH1 by Ausseil (2010). Since dissolved oxygen concentration is influenced by river flow and aeration of the water (Hayward *et al.,* 2003), the higher values during the flood were likely due to the greater flow and water turbulence at the time. The lower limit of dissolved oxygen is important also, and the commonly used guideline value for dissolved oxygen in New Zealand rivers is a lower limit of 6 mg/L (ANZECC & ARMCANZ, 2000), although this lower limit appears to be of no concern in this hapua.

Dissolved oxygen is important since levels below or higher than the tolerance values of biota can have an adverse effect (ANZECC & ARMCANZ, 2000). If water quality values for a site fall out of the guideline range, action should be taken by water managers to ensure that the site returns to a value that is within the guideline range, and to determine what the adverse impacts will be (Davies-Colley, 2000). A study from 2005 to 2008 showed that the average dissolved oxygen for the Hurunui River at State Highway 7 was 11.0 mg/L, and 11.3 mg/L at SH1 (Ausseil, 2010). While the dissolved oxygen concentrations in the lower river do not appear to be of concern, it is possible that dissolved oxygen concentration could fall below 6 mg/L during the summer months when flow is at its lowest and temperatures are warmer.

This would be the most prevalent in areas of the hapua where the flow of water is the least, especially in areas that are ponded.

There was a general decrease in mean dissolved oxygen concentration from high to low tide at each of the sites in both low energy and flood events. The exceptions to this trend was site 1 in the second low energy event when the outlet was located at the southern end of the hapua, site B3 in the first flood when the outlet was located at the northern end, and site 2 in the second flood event when the outlet was located at the southern end of the hapua. Since dissolved oxygen is inversely related to water temperature (Ongley, 1996), the observed results may be a result of the increase in temperature at most of the sites, rather than the influence of the tide. The variation in dissolved oxygen concentration at different stages of the tidal cycle was likely due to a number of factors including the change in water temperature, and the respiration rate and photosynthesis of organisms (Hull *et al.,* 2008; Ongley, 1996).

As well as varying seasonally, dissolved oxygen can also vary daily, therefore it is important that this is taken into consideration (Hull *et al.,* 2008). In a study of dissolved oxygen spatial trends in the Waipara River, the time of day that sampling occurred was shown to have an influence on the dissolved oxygen concentrations (Hayward *et al.,* 2003). Sampling in this study at the Hurunui hapua typically started at the most downstream site (site O) and ended at the most upstream site (site 1). Due to the time to walk to some of the sites, measurements were taken over a couple of hours. The time of sampling at each site was also different for each energy condition due to the time of day that high and low tide occurred. It is likely that these factors would have had an influence on the dissolved oxygen concentration. Dissolved oxygen is also influenced by salinity, solar radiation, wind, and temperature as well as biological activity (Hull *et al.,* 2008). Therefore, it is difficult to conclude whether the observed results are due to spatial variation, the time of sample collection, or due to other interacting factors.

5.5.4 pH

While some of the sites were outside of the guideline values for lowland river sites, all of the sites in all energy conditions were within the 75th percentile guideline of 7.5 to 8.8 specific to the SH1 site on the Hurunui River. pH values for rivers can be outside of the guideline values not because of poor water quality, but because of the geology in the river catchment and surface runoff from agricultural areas (ANZECC & ARMCANZ, 2000; Hayward *et al.,* 2003). The Hurunui River catchment, especially in the lower part of the river, contains sandstone and limestone, which are a source of bicarbonate (Mosley, 2002). This is the likely reason for the values higher more alkaline values than the general guidelines. Because the pH values in the hapua are within the 75th percentile for the SH1 site on the Hurunui River, there is little concern about the alkaline values.

The pH values were generally more alkaline during the low flow events and the storm compared to the floods. The main reasons for the higher values during the low energy events and the storm varies. While algae respiration can have a major influence on pH (Ausseil, 2010; Bookter *et al.,* 2009; Menéndez *et al.,* 2001), this is likely to only have a considerable effect during periods of low flow. Since periphyton photosynthesis increases the pH of the water (Bookter *et al.,* 2009), it is expected that the pH would be the most alkaline in the summer when periphyton mass is at its greatest and the river flow is at its lowest (Hayward *et al.,* 2003). Alternatively, the less alkaline pH values during the flood events was most likely due to the river flow since pH has been shown to be inversely related to discharge (Bishop *et al.,* 2000; Bookter *et al.,* 2009; Davies *et al.,* 1992; Mitchell *et al.,* 1997). This may explain why the pH was less alkaline during the flood events when there was a greater flow, compared to the low energy conditions when pH values were higher. pH was also higher during the storm compared to the flood. This was unlikely due to periphyton growth, instead the elevated pH would have been because of the influence of seawater which has a pH of around 8.2 (ANZECC & ARMCANZ, 2000).

A downstream increase in mean pH occurred in the second low energy event and the two flood events. The opposite trend occurred in the first low energy event. Site O was the exception in both of the low energy events as it had the opposite trend. The decrease in mean pH from sites 1 to B1 in the first low energy event may have been due to the presence of limestone cliffs along the backshore of the hapua. The limestone backshore at site 3, just upstream of site B is visibly eroding (Figure 5.22), distributing limestone chips along the beach and into the water along the hapua backshore. If freshwater is acidic, limestone will break down, however limestone will precipitate instead of erode in seawater since seawater has a high amount of dissolved limestone already. The decrease in pH downstream from sites 1 to B1 indicates that the solubility of limestone is decreasing with distance downstream. The increase in pH at site O1 in the first low energy event was unexpected since seawater inhibits limestone weathering. This increase may have been due to the transport of dissolved limestone chips from the shallows at site 3 through the narrow outlet. Slightly acidic rainfall at this site may result in the chemical weathering of limestone, resulting in the main flow of water passing by site O1 being similar in alkalinity. The lower pH at site B1 may be a result of its location where the main flow of the water containing the calcium carbonate does not reach this area. The increase in pH at sites 3, B5, and O5 during the storm was also unexpected, and this may have been due to the influence of the limestone cliffs along the backshore of the hapua. It is thought that small variations in pH in the Waipara River is due to the difference in geology along its length (Hayward *et al.,* 2003), and it is possible that this is the reason for the observed trends at the Hurunui hapua. The opposite trend during the other events may have been because of the higher flow that caused the influence of limestone erosion along the backshore to be negligible. Without further investigation, it is impossible to conclude the exact reason for the observed trends in pH.

Figure 5.22: Photograph of the eroding limestone backshore of the hapua between sites 3 and B.

There is no discernable trend in pH from high to low tide in both of the low energy and flood events. In the low energy events, there was a general increase in pH from high to low tide, and some of the sites had a decrease. The opposite trend occurred in the two floods. All of the sites had a decrease in pH from high to low tide, although pH remained the same at site B4 in the second flood event.

There is a limited amount of literature about pH in coastal lagoons. While it is difficult to determine the reason for the observed trends in pH in this hapua, it is likely that the presence of periphyton and the geology has a major control on the pH in different areas and in different energy conditions. It is also possible that the trends were influenced by the time of day that sampling occurred since pH can vary throughout the day due to the variation in the uptake of carbon dioxide by periphyton (Hayward *et al.,* 2003; Menéndez *et al.,* 2001). It is expected that spatial differences in pH would be more prevalent during the summer when water temperatures are higher and periphyton growth is greater (Menéndez *et al.,* 2001). The higher water temperature and increased periphyton growth during the summer would result in the water being more alkaline. Because of the possibility of increased periphyton mass with a reduction in flood magnitude and frequency post-dam, a rise in pH outside of the tolerance range of biota could be a significant issue if the dams are to be constructed on this river.

5.6 Summary

This chapter described the current water parameter characteristics in the Hurunui River hapua. This took into account spatial trends, and how the parameters vary at different stages of the tide and in different energy conditions. The water parameters investigated included water temperature, conductivity, dissolved oxygen, and pH.

The results from this investigation showed that the main control on the parameters and spatial trends in this hapua is river flow and the shape of the hapua. Spatial variation was the greatest when the outlet was located at the southern end of the hapua and when ponded areas were present. It appears that the tides have a limited influence on the water parameters. The trends in water parameters varied in the different energy conditions, although the trends varied depending on the parameter.

While some of the parameters were not within the recommended guidelines during some of the events, the exceedance was likely to be temporary. Values outside of the guidelines were probably a reflection of a combination of factors including the catchment geology, waves washing over the barrier, differences in flow throughout the hapua, and the shape of the hapua.

Chapter 6: Nutrients

6.1 Introduction

Nutrients such as nitrogen and phosphorus can vary geographically throughout coastal lagoons (Glibert *et al.,* 2008; Kjerfve & Magill, 1989). Nutrients can be from stormwater, surface runoff, fertilisers, and effluent (Environment Canterbury, 2009). Nutrients can also vary depending on natural factors such as the production of aquatic plants and algae, the pH and temperature of the water, and the geology of the river catchment (Chapman, 1996). While nutrients are essential for aquatic communities, excess concentrations have negative effects, for example the over-production of weeds and algae can alter the water chemistry and environment (Environment Canterbury, 2009). The balance of the input of nutrients is important as it can have a direct influence on productivity, however above a certain level can cause conditions to become eutrophic. The balance of nutrients and the potential for eutrophication in coastal lagoons is controlled by: the flushing of the lagoon, physical dynamics, and the hydrodynamic turnover (Kjerfve & Magill, 1989). Studies have shown that nutrients can also vary over a tidal cycle in lagoon and estuarine systems (Glibert *et al.,* 2008; Kjerfve & Magill, 1989). Tides can often influence the stratification in coastal lagoons, with follow on effects on nutrient concentrations. Because of this, biota may be indirectly affected.

Currently, there is a lack of research on nutrient dynamics in hapua systems. It is unknown if nutrients vary spatially in hapua, and if nutrients are affected by the backwater effect of the tide. The purpose of this chapter is to investigate nutrient concentrations in different energy conditions, in different areas of the hapua, and at different stages of the tide.

The data collected in this chapter was collected over the winter and spring. It is possible that nutrient characteristics in this hapua vary depending on the season. Information from this chapter is used to later evaluate the main controls on nutrient concentrations and spatial trends, and how these could be altered if changes to the river hydrological regime were to occur.

This chapter is divided into 6 sections. Section 6.2 outlines nutrients that are used as indicators of waterway health, section 6.3 describes the methods, section 6.4 the results, section 6.5 an interpretation and discussion of the results, limitations in section 6.6, and a summary in section 6.7.

This chapter addresses the following research objective:

- To examine nutrient concentrations in different areas of the hapua and under different energy conditions.

6.2 Nutrients as indicators of waterway health

In this study, water samples were collected for the analysis of a range of nutrients. Nitrogen and phosphorus are found in a number of different forms, hence a range of forms were tested for. These included: total nitrogen, ammonia nitrogen, nitrate + nitrite nitrogen, total phosphorus, and dissolved reactive phosphorus. Nitrogen can be organic, or inorganic such as ammonia nitrogen (Environment Canterbury, 2009). The most common forms of inorganic nitrogen are nitrate, nitrite, and ammonia (Figure 6.1) (ANZECC & ARMCANZ, 2000). Biological conversions of inorganic nitrogen to organic nitrogen can include: conversion by plants and micro-organisms, reduction of nitrogen gas by miro-organisms, the oxidation of ammonia, decomposition of organic matter which causes organic nitrogen to undergo ammonification, and the reduction of nitrate by bacteria (Chapman, 1996).

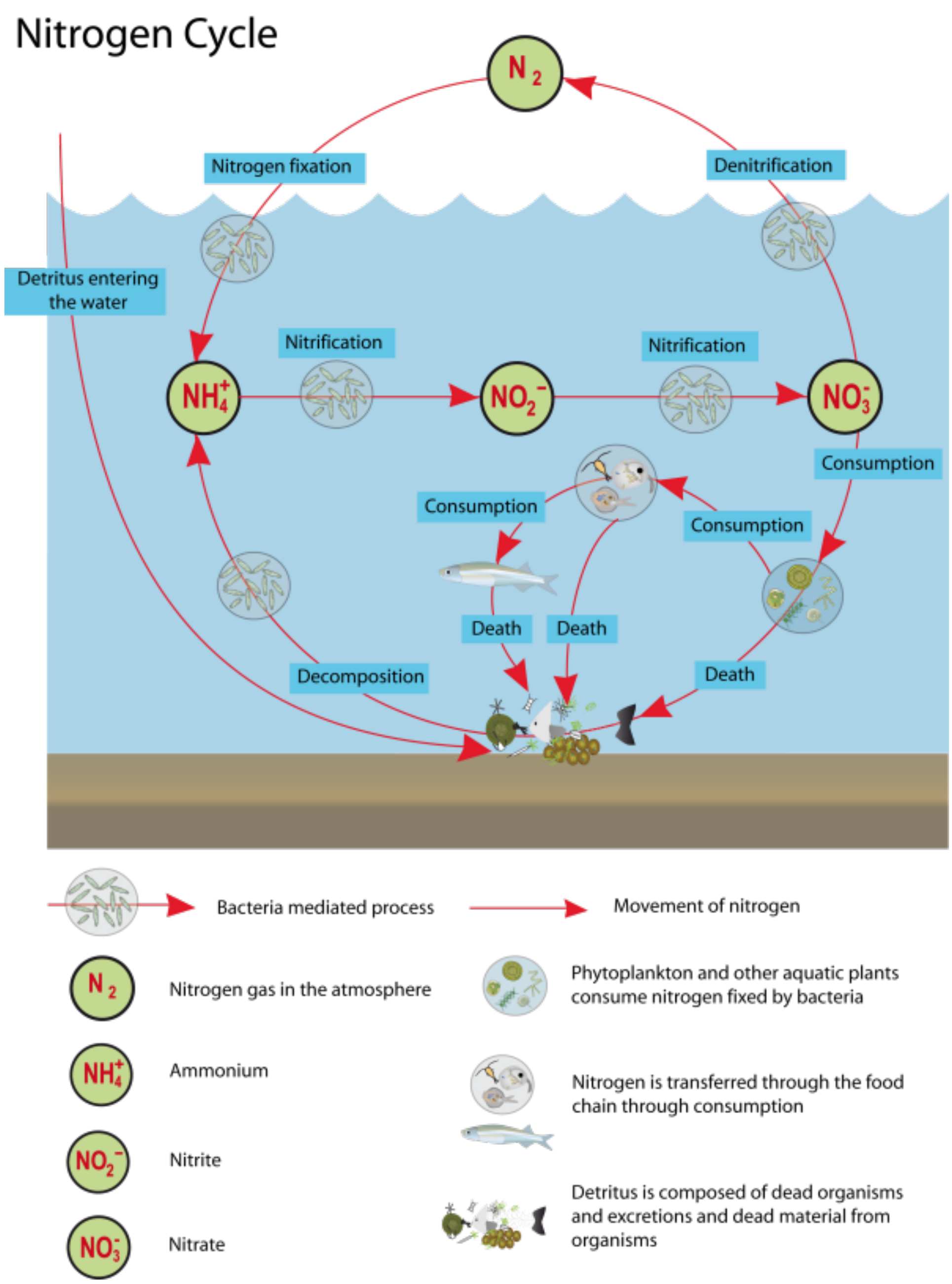


Figure 6.1: The nitrogen cycle (The State of Queensland Government, 2012).

Ammonia nitrogen in waterways comes from both natural and anthropogenic sources (Chapman, 1996; Environment Canterbury, 2009). Above a certain threshold, ammonia nitrogen becomes toxic to aquatic life, especially for fish. The concentration of this nutrient is dependent on the temperature and pH of the water, and is typically around 0.01 g/m^3 in Canterbury Rivers (Environment Canterbury, 2009).

Nitrate is essential for aquatic plants and naturally comes from runoff from the land, plant and animal debris, and from igneous rocks (Chapman, 1996). Inorganic nitrate fertilisers are also a source of nitrate. Nitrate is formed when ammonia is oxidised (Chapman, 1996; Environment Canterbury, 2009). Like ammonia nitrogen, the concentration of nitrate and nitrite is a useful indicator of organic pollution such as sewage and fertilisers (Chapman, 1996).

When testing for phosphorus in water, both dissolved and particulate forms are tested for as phosphorus exists in both forms (ANZECC & ARMCANZ, 2000). Phosphorus in water depends on the dissolved phosphorus species in surface waters and the amount of plant matter in the water (Chapman, 1996). Phosphate is a useful indicator of waterway pollution and can come from a variety of source including fertilisers, runoff from the land and the erosion of phosphate rocks (Figure 6.2) (Britannica Online Encyclopedia, 2013).

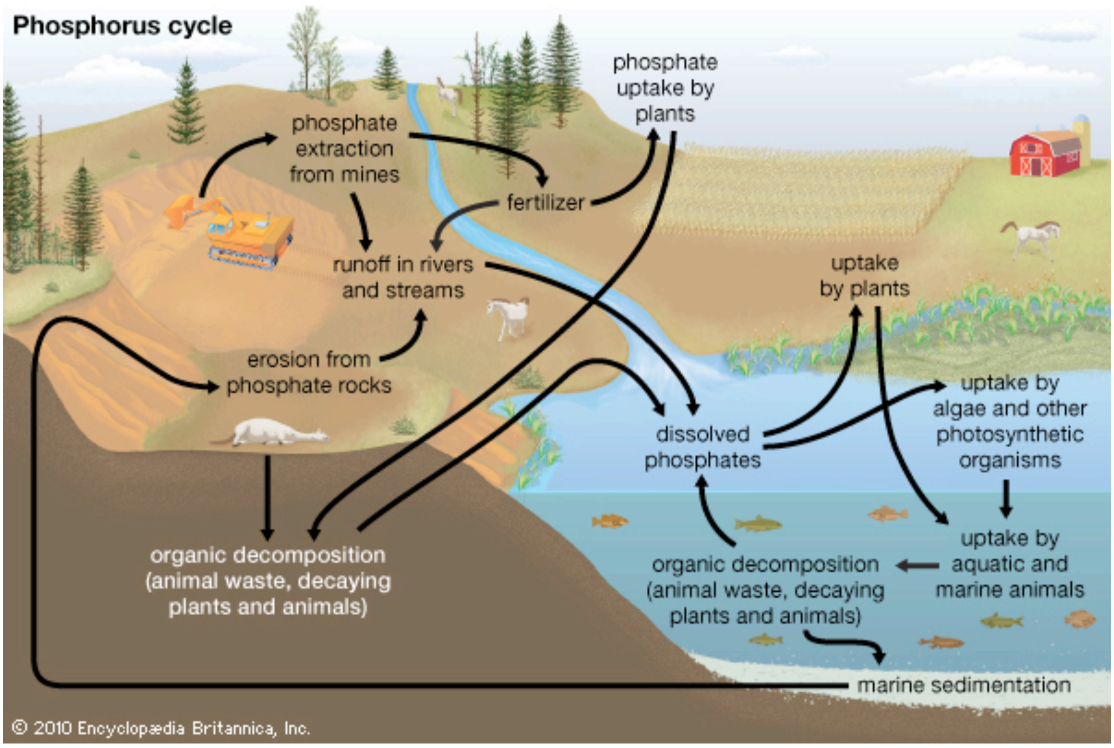


Figure 6.2: The phosphorus cycle (Britannica Online Encyclopedia, 2013).

ANZECC & ARMCANZ (2000) has developed guidelines for a range of nutrients in New Zealand rivers (Table 6.1). The guideline value for ammonia nitrogen is a suggested value since this nutrient varies with pH and temperature (ANZECC & ARMCANZ, 2000). There are currently no specific guidelines for nutrients in hapua ecosystems. Since hapua are mostly freshwater with a limited tidal influence, these guidelines were deemed appropriate for use in this study.

Table 6.1: Guideline values for nutrient concentrations in rivers in New Zealand modified from ANZECC & ARMCANZ (2000).

Nutrient	**Abbreviation**	**Guideline (mg/L)**
Total nitrogen	TN	0.614
Ammonia nitrogen	NH_3N	0.9 (at pH 8 and 20°C)
Nitrate + nitrite nitrogen	NNN	0.444
Total phosphorus	TP	0.033
Dissolved reactive phosphorus	DRP	0.010

The concentration of nutrients in coastal lagoons is sensitive to activities in the lagoon catchment (Lucena *et al.,* 2002; Nixon, 1981; Pereira *et al.,* 2009; Sylaios & Theocharis, 2002). Nutrient concentrations can be directly altered from the change in flow regime and freshwater runoff associated with dams (Sklar & Browder, 1998). Agriculture in their catchments can also influence the concentration of nutrients in coastal lagoons (Sylaios & Theocharis, 2002). Alteration to the concentration of nutrients due to dams can also extend into the marine environment, affecting productivity (Hu *et al.,* 1998; Humborg *et al.,* 2000; Sklar & Browder, 1998; Snoussi *et al.,* 2007). Any change that does occur in the nutrient dynamics and concentration in coastal lagoons will have implications for biota (Comin *et al.,* 1991; Sylaios & Theocharis, 2002).

6.3 Methods

6.3.1 Principles and practices

Nutrients that are commonly tested for in water quality studies include: total nitrogen, nitrate + nitrite nitrogen, ammonia nitrogen, total phosphorus, and dissolved reactive phosphorus (Ausseil, 2010; Hayward, 2001; Mosley, 2002).

Nutrients in water can be measured using a number of methods ranging from basic field tests, to sophisticated field sampling and recording equipment, and laboratory analysis. Continuous or spot measurements of nutrients can be measured *in-situ* with a variety of hand-held instruments such as the multi-probe manta that can be mounted to structures or on a buoy (Glibert *et al.,* 2008). Care must be taken to ensure that deployed equipment for continuous monitoring does not become fouled which can introduce bias to the results. Another method that is commonly used when budgets allow is the analysis of water samples by a laboratory. Laboratory analyses provide low detection limits (Herrera, 1994; Lucena *et al.,* 2002; Pereira *et al.,* 2009). The sampling method that is used depends on the expense of the equipment, the sampling objectives, and the detection limit required.

6.3.2 Sample Collection

Water samples were taken at the same sites as those collected for suspended sediment analysis in Chapter 4 (Figure 2.7 in Chapter 2). Water samples for the analysis of nutrients were taken in different areas of this hapua, in three different energy conditions, and at different stages of the tide during low energy conditions.

Samples were taken in two low energy events, the first on the 13th of July and the second on the 24th of September 2012. During the first low energy event, the outlet was elongated and located to the far north of the hapua (Figure 6.3a). There were no ponded areas and there was a similar flow of water going past each site. The backshore site was labelled B6 and the outlet site O6. During the second low energy event the outlet was located at the southern end and the majority of the hapua was ponded (Figure 6.3b). The backshore site was labelled B2 and the outlet site O2.

During the flood, the main outlet was at the southern end of the hapua, and a secondary outlet was located at the northern end (Figure 6.3c). There was a small ponded area at the northern end that was part of the existent river channel. The backshore site was labelled B7 and the outlet site O7.

The hapua shape and location of the outlet in the storm was similar to the second low energy event, although the outlet was located approximately 20 m further north (Figure 6.3c). The backshore site was labelled B5 and the outlet site O5.

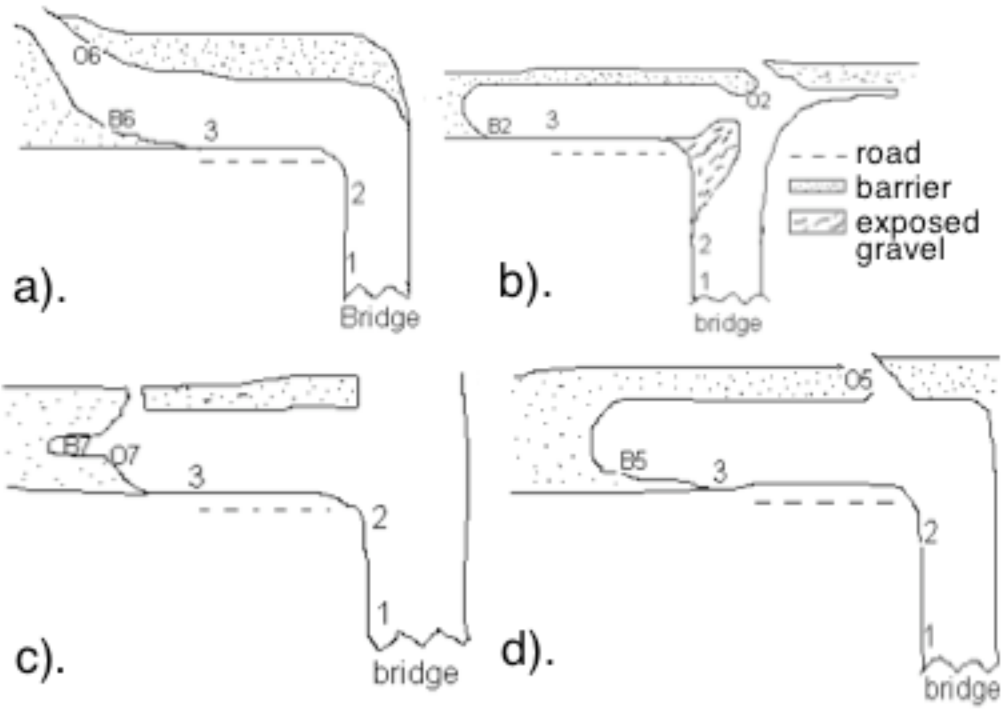


Figure 6.3: Sketches of the antecedent morphology at the time of sampling and the location of the sample sites (not to scale), a) corresponds to low flow conditions on the 13th of July 2012, b) to low flow conditions on the 24th of September 2012, c) to flood conditions on the 2nd of August 2012, and d) to a storm on the 7th of November 2012.

Samples were taken at high, mid, and low tide during the low energy events with the intent of investigating any changes in nutrient concentrations over a falling tide. Because three samples were taken at each site in the low energy events, the results across the tide were averaged to look at spatial trends and differences between the events. Samples were not collected at different stages of the tide in flood and storm conditions for safety reasons. Samples were also not collected at different stages of the tide in these events due to the likelihood of river processes dominating during the flood, and wave processes dominating during the storm. Unlike the samples taken for suspended sediment and water parameters, samples were taken close to the outlet during the flood event due to the shape of the hapua at the time of sampling.

Water samples were collected to test for: total nitrogen, nitrate + nitrite nitrogen, ammonia nitrogen, total phosphorus, and dissolved reactive phosphorus. Samples were taken at knee depth in the middle of the water column using a water sample pole and an acid-cleaned polyethylene bottle. The samples were stored at 4°C until they were processed in the laboratory. The multi-probe *Manta2* was used each time that samples were taken to record water temperature pH, conductivity, and dissolved oxygen. Field conditions at the time of sampling were also noted. These observations included: wind strength, cloud cover, wind direction, and whether there had been rain prior to sampling in the past 24 hours.

6.3.3 Sample and data processing

The water samples were delivered to the Environment Canterbury laboratory within 24 hours of collection. The results were analysed in *Microsoft Excel.* For values below the detection limit, the approach used by Hayward (2001) was used. The "less than" values were classified as a value that was half of the detection limit. The data for the low energy conditions was analysed to determine whether nutrient concentrations changed from high to low tide, and to investigate spatial differences.

6.4 Results

6.4.1 Spatial differences in nutrients and in different energy conditions

6.4.1.1 Total nitrogen

The guideline value for total nitrogen in New Zealand rivers is 0.614 mg/L (ANZECC & ARMCANZ, 2000). The mean concentration of total nitrogen in the low energy events ranged from 0.37 mg/L at site 3 to 0.43 mg/L at site B6 in the first event, and 0.40 mg/L at site 2 to 0.46 mg/L at sites 3 and O2 in the second low energy event (Figure 6.4). The mean concentration of total nitrogen was similar ($P>0.05$) between the two low energy events and there was limited spatial variation in concentration between the sites ($P>0.05$).

The concentration during the flood ranged from 0.35 mg/L at site B7 to 0.96 mg/L at site O7 (Figure 6.4). Site B7 had a much lower concentration of total nitrogen than the other sites and the other energy events. During the flood event, the concentration of total nitrogen was significantly higher than the low energy events and the storm ($P<0.05$).

Total nitrogen concentration ranged from 0.17 mg/L at site 2 to 0.23 mg/L at site 3 during the storm (Figure 6.4). Total nitrogen concentration during the storm was significantly different to the flood and low energy events ($P<0.05$).

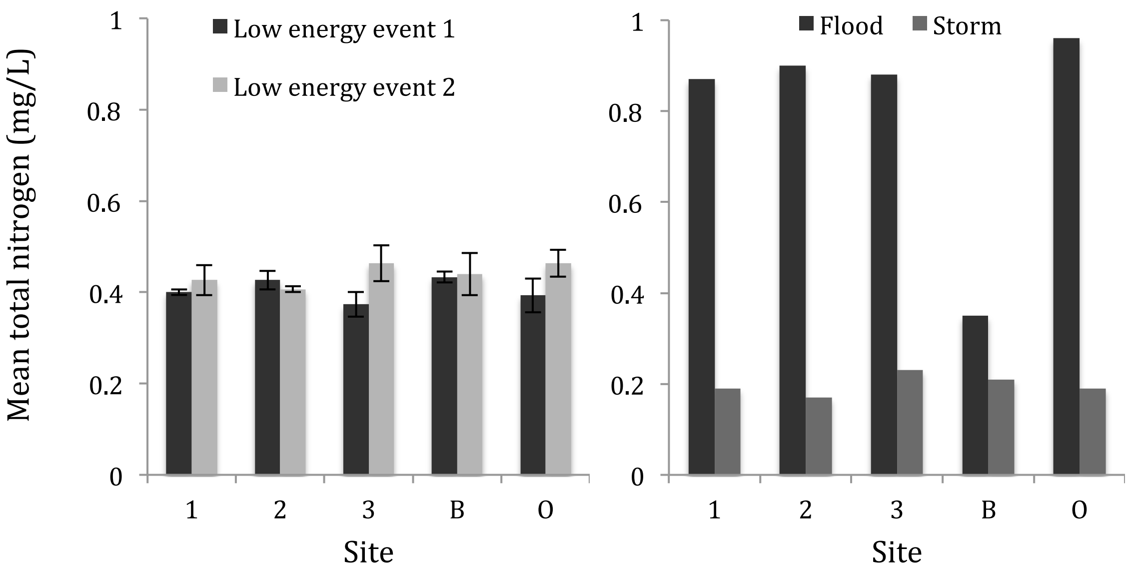


Figure 6.4: Mean total nitrogen (mg/L) over an outgoing tide in two low energy events with error bars (left). Total nitrogen in a flood and storm at each site (right).

6.4.1.2 Ammonia nitrogen

The suggested guideline value for ammonia nitrogen in New Zealand rivers is 0.9 mg/L (ANZECC & ARMCANZ, 2000). Mean ammonia nitrogen concentration was greater in the first low energy event than the second low energy event (Figure 6.5). In the first low energy event, mean ammonia nitrogen concentration ranged from 0.017 mg/L at site 3, to 0.024 mg/L at site B6. In the second low energy event, mean ammonia nitrogen concentration ranged from 0.009 mg/L at site B2 to 0.014 mg/L at site O2. The mean concentration was not significantly different between the sites (P>0.05) in both of the low energy events. Mean ammonia nitrogen concentration was not significantly different between the second low energy event and the storm (P>0.05).

Ammonia nitrogen concentration in the flood ranged from 0.025 mg/L at site 2 to 0.044 mg/L at site O7 (Figure 6.5). Ammonia nitrogen concentration in the storm ranged from 0.006 mg/L at site 1 to 0.013 mg/L at site O5.

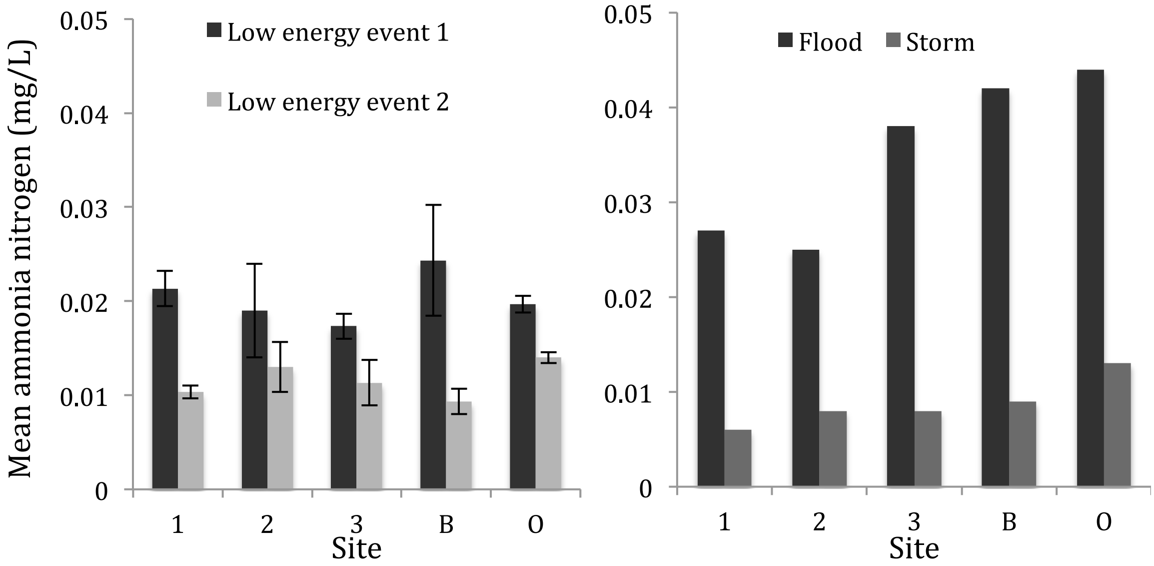


Figure 6.5: Mean ammonia nitrogen (mg/L) over an outgoing tide in two low energy events with error bars (left). Ammonia nitrogen in a flood and storm at each site (right).

6.4.1.3 Nitrate + nitrite nitrogen

The guideline value for nitrate + nitrite nitrogen in New Zealand rivers is 0.444 mg/L (ANZECC & ARMCANZ, 2000). There was a general down stream decrease in mean nitrate + nitrite nitrogen concentration in the first low energy event (Figure 6.6). Site 1 had the highest mean concentration of 0.40 mg/L, and site O6 had the lowest concentration of 0.31 mg/L. There was only 0.09 mg/L difference between sites 1 and O6. In the second low energy event, nitrate + nitrite nitrogen ranged from 0.35 mg/L at site O2 to 0.41 mg/L at site 3. A downstream decrease was not evident in the second low energy event. There was no spatial variation in nitrate + nitrite nitrogen concentration in the two low energy events ($P>0.05$). There was no significant difference in nitrate + nitrite nitrogen concentration between the two low energy events and the flood ($P>0.05$). Nitrate + nitrite nitrogen was significantly different in the storm compared to the other energy events ($P<0.05$).

Nitrate + nitrite nitrogen concentration was not different in the flood event compared to the low energy events (Figure 6.6). However, during the flood event, sites 1, 2, and O7 had a higher concentration of nitrate + nitrite nitrogen than during low energy conditions. Site B7 had a lower concentration during the flood event than the low energy events, and was lower than the other sites during the flood.

Nitrate + nitrite nitrogen concentration ranged from 0.10 mg/L at site B5 to 0.2 mg/L at sites 1 and 2 during the storm (Figure 6.6). The concentration was the lowest at all of the sites during the storm.

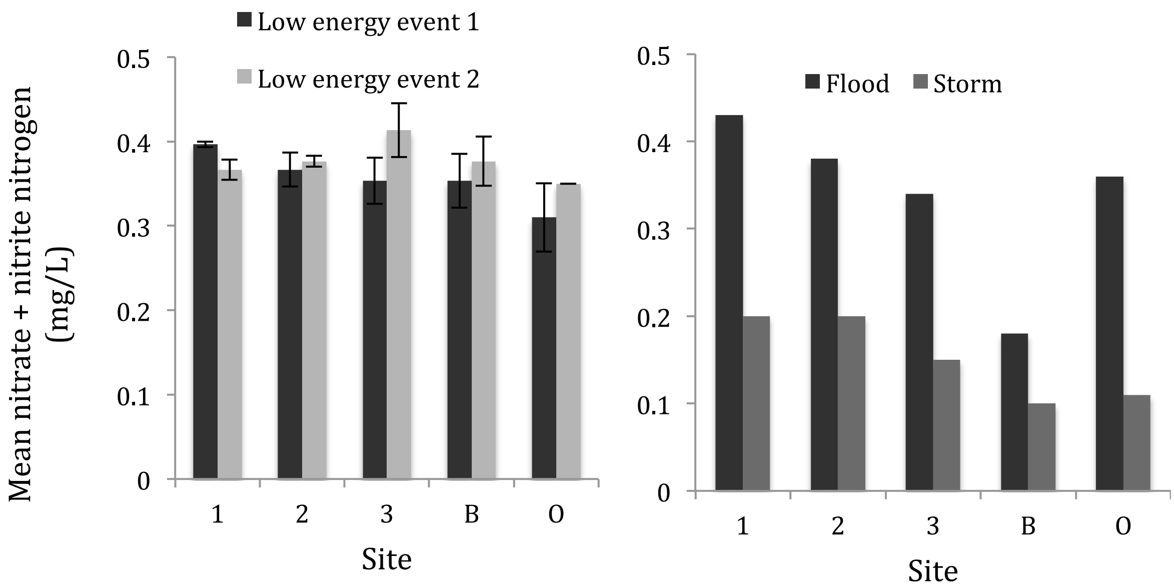


Figure 6.6: Mean nitrate + nitrite nitrogen nitrogen (mg/L) over an outgoing tide in two low energy events with error bars (left). Nitrate + nitrite nitrogen in a flood and storm at each site (right).

6.4.1.4 Total phosphorus

The guideline value for total phosphorus in New Zealand rivers is 0.033 mg/L (ANZECC & ARMCANZ, 2000). Total phosphorus at all of the sites in the first low energy event were less than the 0.008 mg/L detection limit (Figure 6.7). There was no spatial variation in mean total phosphorus concentration between the sites in the first low energy event (P>0.05). Mean total phosphorus concentration was low at all of the sites in the second low energy event, although site 3 had a higher mean concentration compared to the other sites. During the flood, total phosphorus concentration was significantly higher than the low energy events and the storm (P<0.05). Total phosphorus concentration at sites 1, 2, 3, and O7 ranged between 0.73-1.0 mg/L. Site B7 had the lowest concentration of 0.12 mg/L. The concentration of total phosphorus during the storm was the same as the low energy events (P>0.05). During the storm total phosphorus concentration ranged from 0.014 mg/L at site 1 to 0.02 mg/L at site B5.

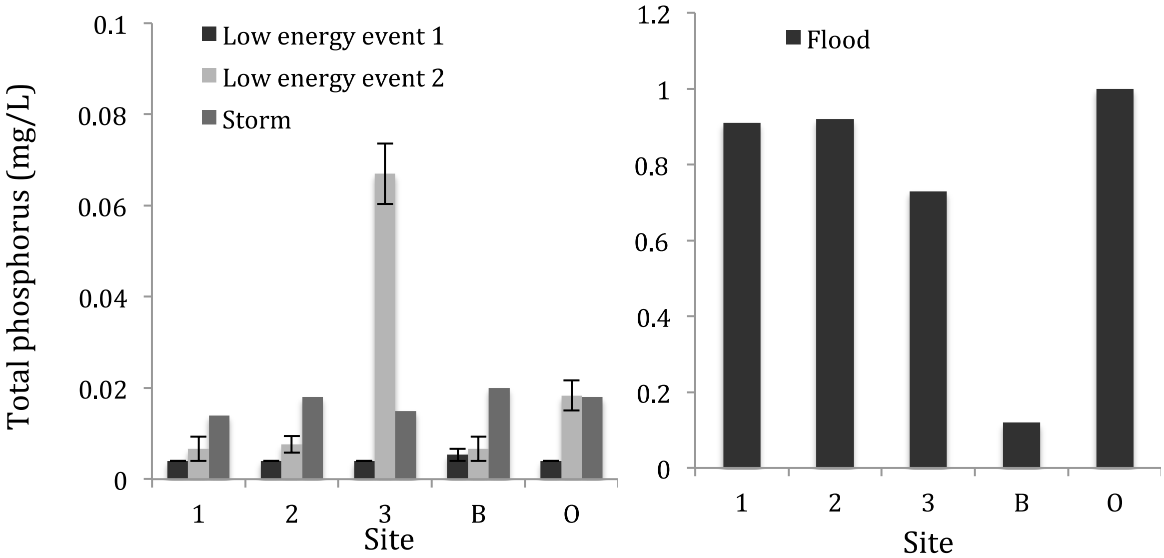


Figure 6.7: Mean total phosphorus (mg/L) over an outgoing tide at each site in two low energy events with error bars and in a storm (left), and total phosphorus at each site in a flood (right). Note the difference in y axis scale between the two plots.

6.4.1.5 Dissolved reactive phosphorus

The guideline value for dissolved reactive phosphorus in New Zealand rivers is 0.010 mg/L (ANZECC & ARMCANZ, 2000). The concentration of mean dissolved reactive phosphorus in the first low energy event ranged from 0.0017 mg/L at site 1 to 0.0042 mg/L at site B6 (Figure 6.8). Mean dissolved reactive phosphorus concentration in the second low energy event ranged from 0.0017 mg/L at site B2 to 0.0083 at site 3. The mean concentration at site 3 was higher than at the other sites. There was no spatial variation in dissolved reactive phosphorus in both of the low energy events and the storm ($P>0.05$).

Dissolved reactive phosphorus concentration was significantly higher in the flood than the low energy events and the storm ($P<0.05$), and the spatial variation was greater (Figure 6.8). During the flood event, concentration ranged from 0.036 mg/L at site O7 to 0.02 mg/L at site 1.

During the storm, dissolved reactive phosphorus concentration ranged from 0.003 mg/L at sites 1 and 3 to 0.007 mg/L at site 2 (Figure 6.8). The concentration during the storm was similar to the low energy events.

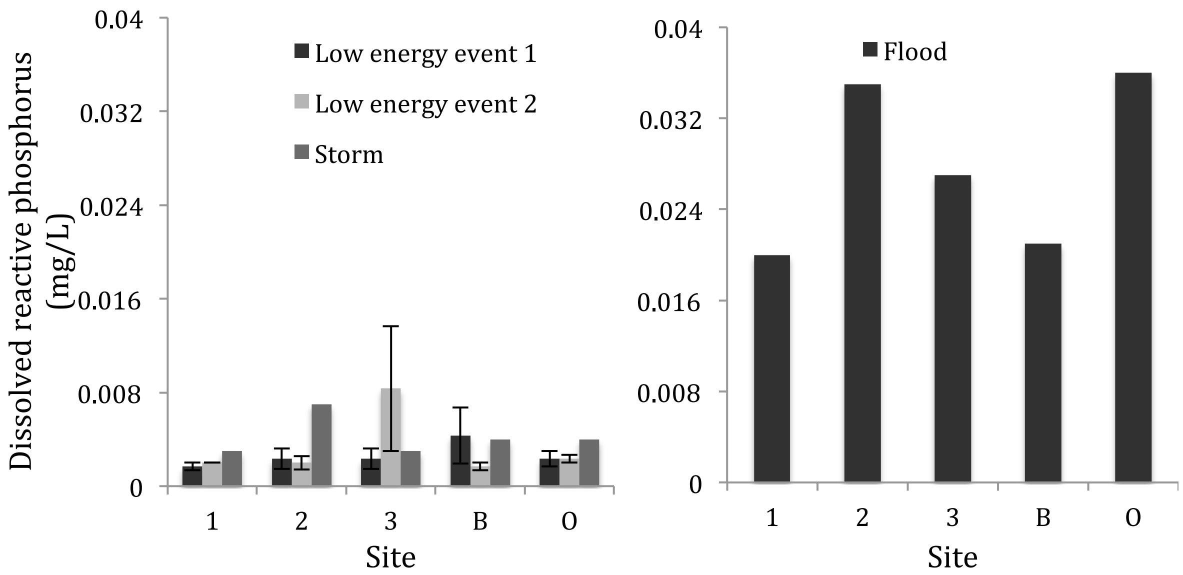


Figure 6.8: Mean dissolved reactive phosphorus (mg/L) over an outgoing tide at each site in two low energy events with error bars, and total phosphorus at each site in a storm (left). Dissolved reactive phosphorus in a flood at each site (right).

6.4.2 Tidal effect on nutrients

6.4.2.1 Total nitrogen

The results were variable for the change in total nitrogen concentration from high to low tide in the first low energy event (Figure 6.9). Sites 1 and 3 had an increase, whereas sites 2, B6, and O6 had a decrease in concentration from high to low tide. There was less variation in the concentration of total nitrogen between the sites at low tide compared to high tide.

During the second low energy event, there was an increase in total nitrogen concentration from high to low tide at sites 2, 3, and B2, and a decrease at sites 1, and O2 (Figure 6.9).

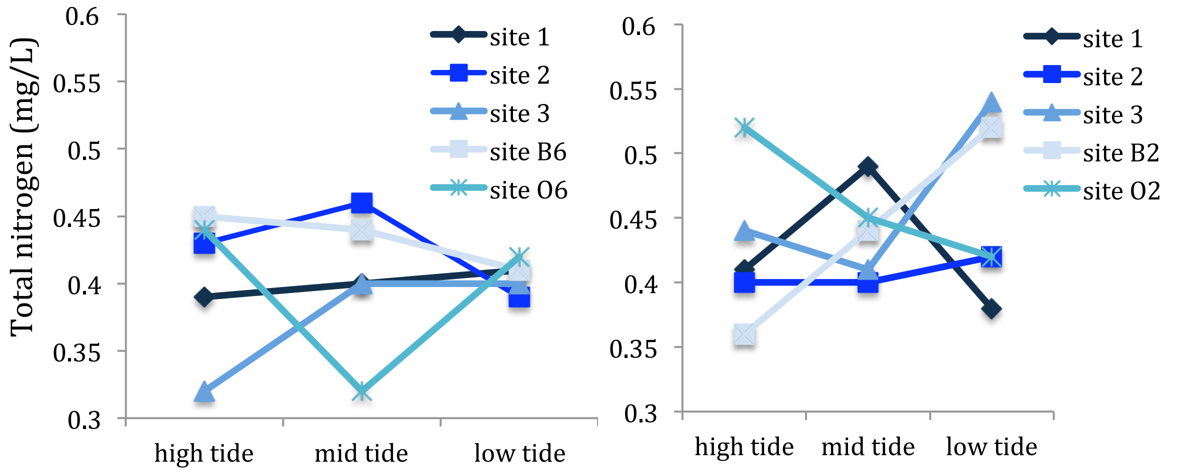


Figure 6.9: Total nitrogen (mg/L) at each site at different stages of the tide in the first low energy event (left), and in the second low energy event (right).

6.4.2.2 Ammonia nitrogen

In the first low energy event there was a decrease in ammonia nitrogen concentration from high to low tide at sites 1, B6, and O6 (Figure 6.10). There was no change in concentration at sites 2 and 3. There was less variation in ammonia nitrogen concentration between the sites at low tide compared to high tide.

In the second low energy event, there was an increase in ammonia nitrogen concentration from high to low tide at site O2, a decrease at sites 2 and 3, and no change at sites 1 and B2 (Figure 6.10).

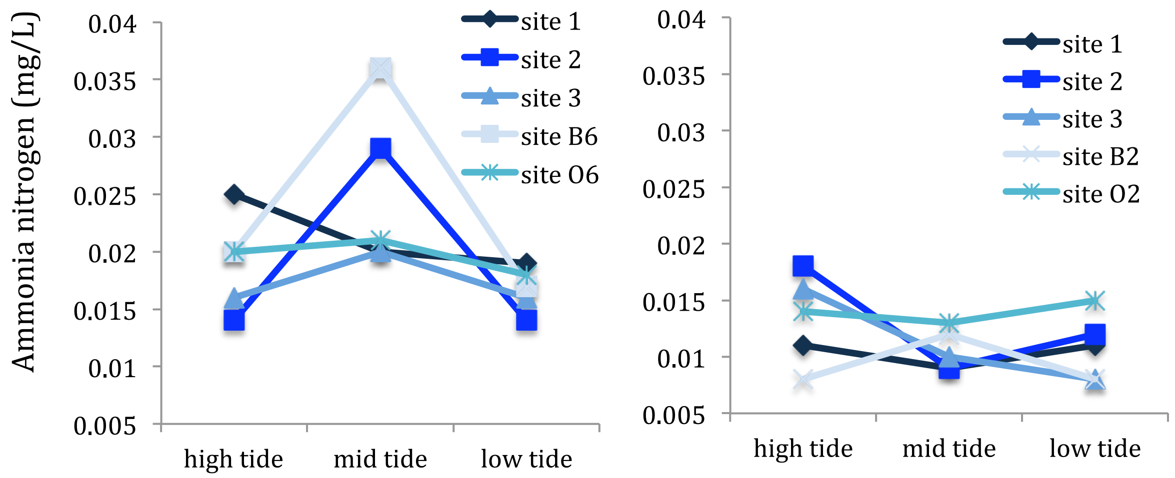


Figure 6.10: Ammonia nitrogen (mg/L) at each site at different stages of the tide in the first low energy event (left), and in the second low energy event (right).

6.4.2.3 Nitrate + nitrite nitrogen

In the first low energy event, there was an increase in nitrate + nitrite nitrogen concentration at all of the sites from high to low tide (Figure 6.11). The exception was site 1 which had no change in concentration from high to low tide. There was less variation in nitrate + nitrite nitrogen concentration between the sites at low tide compared to high tide.

During the second low energy conditions there was an increase in nitrate + nitrate nitrogen concentration from high to low tide at sites 1, 3, and B2, a decrease at site 2, and no change at site O2 (Figure 6.11).

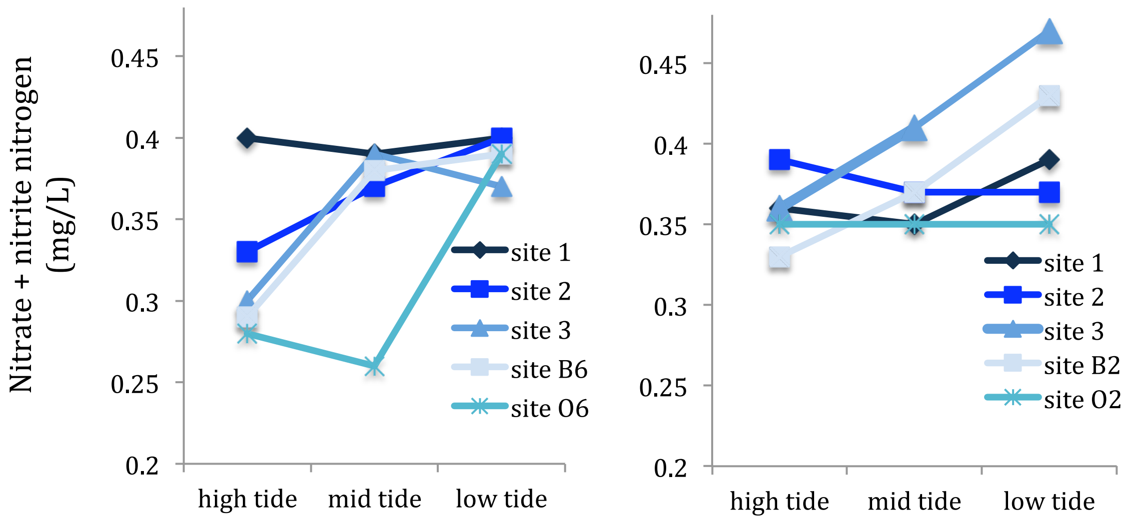


Figure 6.11: Nitrate + nitrite nitrogen (mg/L) at each site at different stages of the tide in the second low energy event (left), and in the second low energy event (right).

6.4.2.4 Total phosphorus

In the first low energy event, the concentration of total phosphorus was below the detection limit at most of the sites. During the second low energy event, there was an increase in concentration from high to low tide at sites 2, 3, and O2, a decrease at site 1, and no change at site B2 (Figure 6.12). Total phosphorus concentration varied more at low tide compared to high tide.

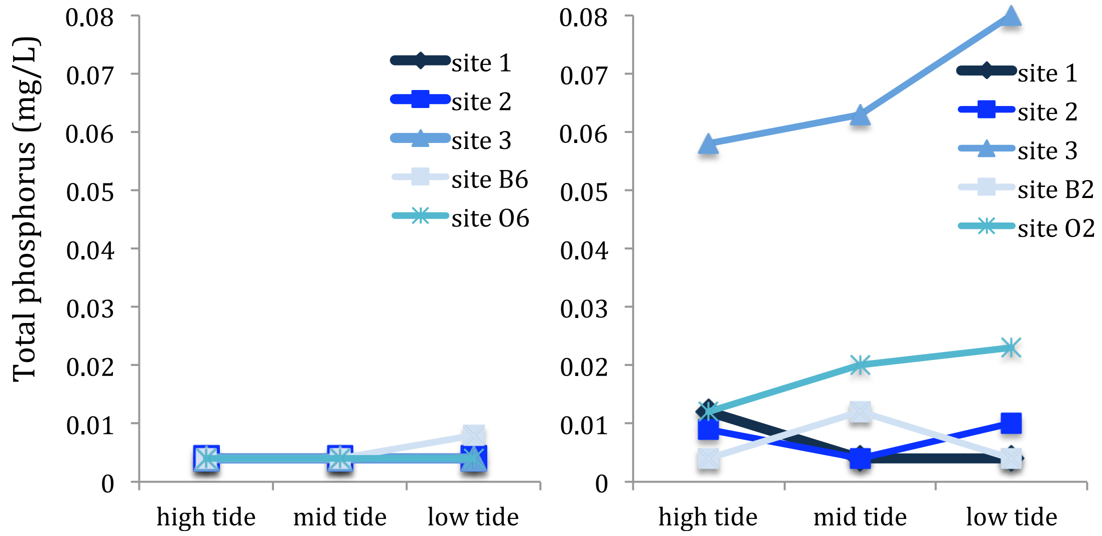


Figure 6.12: Total phosphorus (mg/L) at each site at different stages of the tide in the first low energy event (left), and in the second low energy event (right).

6.4.2.5 Dissolved reactive phosphorus

In the first low energy event, there was a decrease in dissolved reactive phosphorus concentration at all of the sites from high to low tide except for site 1 which had a decrease (Figure 6.13).

In the second low energy event, there was an increase in dissolved reactive phosphorus concentration from high to low tide at sites 2 and B2, a decrease at sites 3 and O2, and no change at site 1 (Figure 6.13).

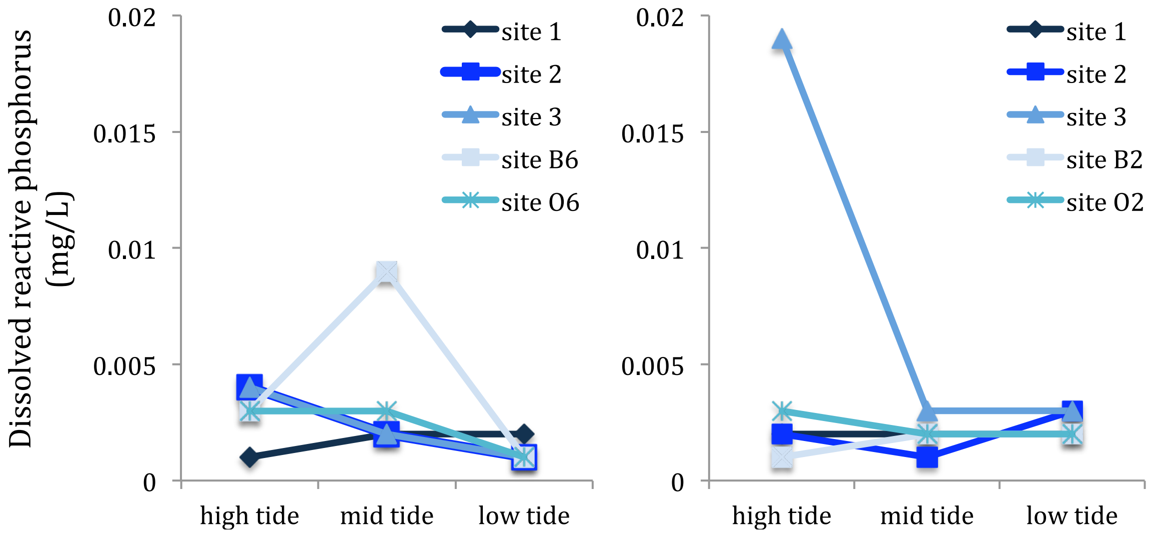


Figure 6.13: Dissolved reactive phosphorus (mg/L) at each site at different stages of the tide in the first low energy event (left), and in the second low energy event (right).

6.5 Interpretation and discussion of results

6.5.1 Spatial and temporal differences in nutrients

During the low energy events, there was little to no variation in the concentration of nutrients between the sites despite the shape of the hapua being considerably different in morphology, and thus a variation in the distribution and mixing of river and seawater. During the first event the outlet was located at the northern end of the hapua, and the flow at each site was relatively similar. However, during the second low energy event the outlet was at the southern end, and sites 3 and 4 were isolated from the main current of the river. It was expected that spatial differences would exist during the second event due to the difference in the shape of the hapua, and the flow at each site. However, because these expected differences did not occur, it is concluded that the shape of the hapua has little or no influence on the concentration of nutrients in different areas of the hapua in low energy conditions.

This conclusion is further supported by the small difference in concentration of most of the nutrients at each site between the two low energy events. For instance, all of the sites had a lower concentration of ammonia nitrogen in the second low energy event compared to the first event. If the shape of the hapua influenced ammonia nitrogen, spatial differences would have been more evident in the second low energy event due to the shape of the hapua. The absence of spatial differences in the second low energy event may have been due to the indirect influence of the tides. At high tide, water flowed into the ponded area that was isolated from the main current (Figure 6.14), and flowed out of this area at low tide (Figure 6.15). As a result, there was a significant change in water level in the ponded main area of the hapua. This movement of water would likely have assisted in the mixing of the water column and resulted in the nutrients being reasonably evenly distributed.

Figure 6.14: Southern end of the hapua close to high tide.

Figure 6.15: Southern end of the hapua close to low tide.

Although the concentration of nutrients varied little between the sites in the low energy events, there were some exceptions. During the first low energy event, the concentration of ammonia nitrogen at site B6 was the highest of all the sites, even though the flow past each site was similar. This may have been due to the input from two small streams located between sites 3 and B (Figure 6.16). These streams run through farmland adjacent to the hapua backshore. Images taken over 2 hours with the thermal camera show a difference in the surface water temperature in the vicinity of site B. It is unlikely that there was any tidal influence since the outlet was located further north. The change in surface water temperature, and the higher concentration of ammonia nitrogen at this site may have been due to groundwater and stream inputs. During the second low energy event there was also a much higher concentration of total phosphorus and dissolved reactive phosphorus at site 3 compared to the other sites. This is attributed to the wind driven resuspension of fine sediment from the hapua bottom. This site was much more turbid than the other sites, hence the greater concentration of total phosphorus and dissolved reactive phosphorus.

Figure 6.16: Two small streams that flow into the hapua along the backshore of the hapua between sites 3 and B. The stream on the left had no water at the time of the image capture, but sometimes has water.

The spatial trends in nutrients in this hapua in low energy conditions are likely to be controlled by both external and internal processes. The absence of spatial differences in the low energy events may have been due to internal processes occurring within the hapua. These could include: primary production, mineralization, plant and animal recycling, and sediment processes (Herrera, 1994; Lucena *et al.,* 2002; Newton *et al.,* 2003). Unlike some lagoons that can have a relationship between nutrient concentrations and seawater influence (Newton *et al.,* 2003), it is unlikely that this relationship occurs in this lagoon.

Algae were observed along most of the backshore of the hapua. This could influence the concentration of nutrients within the lagoon because of the feedback effects on the chemistry of the water (Sklar & Browder, 1998). The absence of spatial differences in the low energy conditions could also be due to a high enough flow in the hapua that results in a small water residence time. This would prevent any significant spatial differences from occurring.

As mentioned above, spatial differences in the concentration of nutrients could possibly be related to external stream inputs. Spatial variation can be due to internal processes involving wind driven circulation and resuspension of fine sediment. It is concluded that when wind driven circulation is not significant, the main control on the spatial variability in nutrient concentrations in low energy conditions is the mixing of water and flow at each site which is determined by the shape of the hapua.

During the storm, the concentration of some of the nutrients varied spatially, while there was a limited amount of spatial variation in concentration for the other nutrients. There was a limited amount of spatial variation in total nitrogen and total phosphorus concentration. Ammonia nitrogen concentration had a slight downstream increase, and nitrate + nitrite nitrogen concentration had a slight downstream decrease. Dissolved reactive phosphorus concentration was similar at all of the sites except for site 2 which had a much higher concentration compared to the other sites. It is unknown why this nutrient was much higher at site 2 compared to the other sites.

During the second low energy event a strong wind caused fine sediment on the bottom of the hapua to be resuspended. As a result, the concentration of total phosphorus and dissolved reactive phosphorus was higher in the affected area compared to the other sites. Disturbance of fine sediment on the hapua bottom during the storm resulted in an increase in the concentration of total phosphorus and dissolved reactive phosphorus. It is also concluded that like the low energy events, the shape of the hapua has a minimal influence on the concentration of nutrients throughout the hapua during storm conditions. This is probably due to the relatively similar marine influence throughout the hapua. Spatial differences can occur during storms, but are less evident than the differences that occur during floods.

In contrast to the low energy events and the storm, the flow of the river and the shape of the hapua had an influence on the spatial trends and the concentration of nutrients during flood conditions. During the flood, the main outlet was at the southern end of the hapua, and a smaller secondary outlet remained at the northern end. The outlet at the northern end had migrated further south from its position to the week's prior, resulting in a small ponded area. As a result, this site (site B7) was distinctly different to the other sites. This site had a much lower concentration of nitrate + nitrite nitrogen, total phosphorus, and total nitrogen compared to the other sites. The low concentration of these nutrients was likely due to the isolation from the main current during the flood. The minimal current and isolation in this area would have prevented water from being transported there. This demonstrates that the shape of the hapua, and the flow at each site has a control over the spatial variation in nutrient concentrations during flood conditions. It is therefore concluded that spatial trends in nutrients at this hapua are evident in flood conditions, especially when the shape of the hapua causes the flow to vary throughout the hapua. It is also evident that ponded sites that are away from the main current of the river are unaffected by the increase in nutrient concentrations in response to the flood. External processes, rather than internal ones are the major control on nutrients during flood conditions.

Although there was a minimal amount of spatial variation in the concentration of nutrients in the second low energy event when the majority of the hapua was isolated from the main current, there is still the potential for spatial differences to exist during low energy conditions. In the second low energy event, it is likely that the change in lagoon level through the day allowed for the water to be well mixed, preventing significant spatial differences to exist. However during the flood, the ponded area had a different concentration of some nutrients compared to the other sites. This demonstrates that if the ponded areas are not influenced by the flow of the river, and do not experience a change in water level in response to the tide, the concentration of nutrients in this area will most likely be lower than other areas throughout the lagoon. This would consequently have implications for biota in the ponded area since the nutrient levels would be different.

As well as spatial differences depending on the shape of the hapua and the energy condition, it is possible the amount of spatial variation in nutrients in this hapua varies with the seasons. It is typical for spatial differences in nutrient concentrations within temperate coastal lagoons to exist, although variations are often influenced by the seasons, chemical parameters, river discharge, and the degree of marine influence (Herrera, 1994; Ho & Barrett, 1977; Marcovecchio *et al.,* 2006; Newton *et al.,* 2003; Nixon, 1981; Pereira *et al.,* 2009). Any relationship between these factors must be understood to adequately understand spatial variation in chemical and biological parameters in coastal lagoons, and for appropriate management to be developed (Herrera, 1994; Pereira *et al.,* 2009). Seasons can influence spatial heterogeneity because of the changes in wind, rainfall, evaporation, and day light hours throughout the year (Caffrey & Day, 1986; Herrera, 1994; Ho & Barrett, 1977; Marcovecchio *et al.,* 2006; Sylaios & Theocharis, 2002). Seasonal differences in nutrients can also be related to the phytoplankton biological cycle, and the variation in chlorophyll *a* concentration throughout the year (Marcovecchio *et al.,* 2006). It is likely that the spatial variation and concentration of nutrients varies throughout the year in response to variation in river flow and the irrigation season in the Hurunui River catchment.

Although the sample size was not large enough to investigate the relationship between nutrient concentration and salinity in the present study, it is likely that the spatial variation in nutrient concentrations in this hapua is partially due to this relationship. An inverse relationship between these parameters was observed in all of the events excluding the second low energy event. Conductivity concentration increased from site 1 to B, and nitrate + nitrite nitrogen concentration decreased from site 1 to B during the flood. This is further supported by the general downward trend in nitrate + nitrite nitrogen concentration from sites 1 to O6 and a general upward trend in conductivity from sites 1 to O6 during the first low energy event. During the storm, sites 1 and 2 had higher concentration of nitrate + nitrite nitrogen and lower salinity compared to the other sites. The inverse relationship between conductivity and nutrient concentrations was particularly evident at site B7 during the flood. The conductivity concentration in this ponded site was much higher than the other sites. The conductivity concentration at this site was 31710 uS/cm, compared to around 80 to 250 uS/cm at the other sites, and the concentration of total phosphorus, nitrate + nitrite nitrogen and total nitrogen was much lower compared to the other sites. This indicates a saltwater influence. In two separate studies of coastal lagoons, areas that were lower in salinity had higher values of nitrate (Herrera, 1994; Sylaios & Theocharis, 2002). Total phosphorus can also be inversely correlated to salinity (Caffrey & Day, 1986;

Pereira *et al.,* 2009; Sylaios & Theocharis, 2002). It is evident that while the hydrological regime does have an important role in the spatial distribution of chemical and biological characteristics (Comin *et al.,* 1991; Herrera, 1994; Sylaios & Theocharis, 2002), the interaction with other water quality parameters must not be ignored.

Most of the sites had much higher nutrient concentrations during the flood compared to the low energy events and the storm. Due to the morphology at the time of sampling, site B7 had a lower concentration of some of the nutrients compared to the concentration in the low energy events and the other sites. The higher concentrations during the flood were expected and are unlikely to have a major control on the functioning of the hapua since the elevated levels were short in duration. Some of the sites during the flood had nutrient concentrations that exceeded the guideline values set by ANZECC & ARMCANZ (2000). Exceedance of the guidelines was typical in the flood (Table 6.2). All of the sites except for site B7 exceeded the guideline value of 0.614 mg/L for total nitrogen (0.35-0.96 mg/L). The guideline value of 0.34 mg/L for coastal lagoons and lakes in the Canterbury Region for total nitrogen was also exceeded. Total phosphorus concentrations (0.12-1.0 mg/L) exceeded the ANZECC and ARMCANZ (2000) guideline value of 0.033 mg/L and the guideline value of 0.02 mg/L for coastal lakes and lagoons in the Canterbury Region (Environment Canterbury, 2011a). Dissolved reactive phosphorus concentration (0.02-0.036 mg/L) also exceeded the ANZECC and ARMCANZ (2000) guideline value of 0.01 mg/L, and the guideline value of 0.003 mg/L for lower lake-fed rivers in the Canterbury Region (Environment Canterbury, 2011a) at all of the sites. Nitrate + nitrite nitrogen concentrations at all sites were below the guideline value of 0.444 mg/L (0.18-0.43 mg/L). Ammonia nitrogen concentrations were below the guideline value of 0.9 mg/L (0.025-0.044 mg/L) during the flood event.

Table 6.2: Summary of the nutrient concentrations and sites that exceeded and did not exceed the guidelines set by ANZECC & ARMCANZ (2000) during the flood (√ exceedance of the guideline, X within the guideline).

Site	**Nutrients (mg/L)**				
	TN	**NH_3N**	**NNN**	**TP**	**DRP**
1	0.87 √	0.027 X	0.43 X	0.91 √	0.02 √
2	0.90 √	0.025 X	0.38 X	0.92 √	0.035 √
3	0.88 √	0.038 X	0.34 X	0.73 √	0.027 √
B7	0.35 X	0.042 X	0.18 X	0.12 √	0.021 √
O7	0.96 √	0.044 X	0.36 X	1.0 √	0.036 √
Guideline (mg/L)	0.614	0.9 (at pH 8 and 20°C)	0.444	0.033	0.010

At all of the sites during the low energy conditions all nutrient concentrations were consistently below the guideline values for all of the nutrients. The results indicate that at the time of sampling, this hapua was in a healthy state in terms of nutrient concentrations in relation to the guidelines, especially during the low energy and storm events. However, this does not mean that this hapua is in a relatively healthy state year round, and that the long-term trends should be disregarded. Nutrient concentrations in this river are higher in the irrigation season, especially in the lower river. For instance, dissolved reactive phosphorus concentration is much higher during the irrigation season, with 50-80% of the annual load occurring during this period (Ausseil, 2010). The low energy events in this study were sampled out of the irrigation season, so it is likely that the nutrient concentrations would be higher in low flow conditions during the irrigation season due to the greater runoff from agricultural areas.

Despite the likelihood of the concentration of nutrients in this hapua being below the guidelines for the majority of the time, a downstream increase in the concentration of nutrients for this river has been identified. The concentration of nutrients in the low energy events except dissolved reactive phosphorus, were higher at the hapua compared to the mean annual values from 2005 to 2008 recorded at the State Highway 7 site (Table 6.3) (Ausseil, 2010). There is the potential for a continued increase in the concentration of nutrients if agricultural activity and surface runoff in the river catchment intensifies. There is also the potential for the concentration of nutrients to increase at the river mouth if the water parameters are altered as a result of low flows since nutrients can be affected by some chemical parameters (ANZECC & ARMCANZ, 2000). For instance, the higher the temperature, the greater the toxicity of ammonia nitrogen, and the greater the impact on biota (ANZECC & ARMCANZ, 2000). The water temperature in ponded areas was typically higher, and even though the concentration of nutrients was not different to the other sites in the low energy conditions, there is the potential for the effect of these nutrients to change if there is a temperature increase. Any change that does occur in relation to the timing and duration of nutrient inputs will have implications for biota and primary production in the hapua (Caffrey & Day, 1986). This highlights the importance of determining what biota are present within this lagoon.

Table 6.3: Mean concentration (mg/L) of nutrients in the two low energy events at SH1 from 2005 to 2008 (Ausseil, 2010, p. 33).

Nutrient	**Mean (mg/L)**		
	Low energy event 1	**Low energy event 2**	**2005-2008 at SH1**
TN	0.41	0.44	0.40
NH_3N	0.020	0.012	0.012
NNN	0.36	0.38	0.32
TP	0.004	0.021	0.0
DRP	0.003	0.003	0.004

There are a number of likely reasons for the difference in concentration of nutrients in the different energy events. Nutrient levels in coastal lagoons are influenced both spatially and temporally by: surface runoff, river discharge, atmospheric fallout, tides, and biological activity (Nixon, 1981). The greater concentration for most nutrients at most of the sites during the flood is because of the greater surface runoff from the agricultural areas in the catchment in combination with the greater discharge. The Hurunui River catchment has intensive dairy farming especially on the plains that are adjacent to the river in the Culverden Basin (Ausseil, 2010). This farming, in combination with border dyke irrigation that has significant surface runoff, has resulted in concerns since the late 1990s about the decrease in the water quality of the surrounding waterways (Ausseil, 2010). During flood events, surface runoff and drainage from the agricultural land increases, so this is the likely reason for the higher concentration of nutrients during the flood event compared to the low energy event. The influence of flow on the concentration of nutrients was evident during the flood as the ponded site B had a much lower concentration of some nutrients compared to the other sites that experienced a much higher flow. This same relationship between high flow and high nutrients such as nitrate has also been observed in both coastal lagoons and estuaries (Caffrey & Day, 1986; Ho & Barrett, 1977; Marcovecchio *et al.,* 2006; Nixon, 1981).

The mean concentration of nutrients in the low energy events and the storm were lower than the flood. Total nitrogen, ammonia nitrogen and nitrate + nitrite nitrogen concentration were lower in the storm (0.2, 0.009, and 0.15 mg/L respectively) than the low energy events (0.42 mg/L, 0.016 mg/L, and 0.37 mg/L). The lower concentration of these nutrients during the storm may have been due to the increase in water level in the lagoon as waves washed over the barrier. The actual rise in water level was not measured due to a faulty water level recorder. This increase in water level would have diluted the nutrients. The general inverse relationship between nitrogen and salinity during the storm was consistent with the results from Herrera (1994) and Sylaios (2002) who showed the same relationship. Sites B5 and O5 had the highest salinity (7.7 and 7.3 ppt), and in general the lowest nitrogen concentrations.

The opposite occurred for total phosphorus and dissolved reactive phosphorus. These nutrients were generally higher in concentration during the storm compared to both of the low energy events. The only exception was at the sites that were influenced by wind driven resuspension of fine sediment from the hapua bed during the second low energy event. The higher values of these nutrients compared to the low energy event was probably because of the disturbance of the hapua bed by the waves washing over the barrier into the lagoon, and from the movement of fine sediment previously deposited on the barrier from floods into the lagoon by the waves where it remained in suspension.

6.5.2 Tidal backwater effect on nutrients

Hapua have no direct tidal influence, but do have a backwater effect where water backs up in the lagoon at high tide due to a slower outflow (Hart, 1999). The trends in the nutrients over a falling tide show the influence of both freshwater and the effect of wind driven resuspension of fine sediment on the bed of the hapua. There was less variation in the concentration of total nitrogen, ammonia nitrogen, and nitrate + nitrite nitrogen between the sites at low tide compared to high tide in the first low energy event. This shows that there is a greater freshwater influence at low tide as the backwater effect at low tide compared to high tide is less. During the second low energy event, there was more spatial variation in the concentration of total nitrogen, ammonia nitrogen, and nitrate + nitrite nitrogen at low tide. This was likely due to the shape of the hapua and the wind driven resuspension of fine sediment from the hapua bed at some of the sites. For instance, at low tide, sites 3 and B2 had a higher concentration of total nitrogen than the concentration at the other sites. This higher concentration could have been due to the turbid water at sites 3 and B2. This shows that the tide has a greater influence on nutrients in this hapua when the outlet is located at the northern end of the hapua, and when wind driven resuspension of fine sediment occurs.

While nitrogen appeared to be influenced by freshwater inputs, phosphorus appeared to be unaffected. Phosphorus was affected by the stirring up of sediment on the hapua bed during the second low energy event. This was shown by the much higher concentration of total phosphorus at site 3 compared to the other sites, and the increase in concentration from high to low tide. The greater difference in total phosphorus between the sites during the second low energy event at low tide would have been due to the increase in turbidity at around mid tide, which resulted in greater spatial differences compared to at high tide. Dissolved reactive phosphorus did not show this same trend and it is known why this was the case.

Tides can influence nutrients in coastal lagoons (Pereira *et al.,* 2009). In a study by Pereira (2009), there was a difference in nutrients from high to low tide, indicating that incoming seawater diluted the concentration of nutrients. Although there is no tidal prism in hapua (Hart, 2007), this study indicates that nitrogen is influenced by the indirect backwater effect of the tide. At high tide, the flow of water out of the hapua is reduced, and water backs up, causing the water level in the hapua to rise (Kirk, 1991). As the tide falls and the lagoon drains, the outflow increases, and the spatial variation in nitrogen concentration between the sites reduces.

Tidal influence on nutrients can sometimes be demonstrated by a relationship between conductivity and salinity with nutrients (Lucena *et al.,* 2002; Pereira *et al.,* 2009). However, in this study there was a minimal relationship between conductivity and the nutrients (R^2<0.22). This is likely due to the limited data set used to investigate this relationship. It is possible that there is no direct influence of saltwater on the concentration of nutrients. This is consistent with the findings of Hart (1999) who showed that there is no increase in salinity across tidal cycles, except during storms at the Hurunui River mouth.

The conclusion that there is little influence of the tide during low energy conditions on the concentration of nutrients throughout this hapua is further supported by the lack of a consistent trend in the variability at each site from high to low tide. For instance, in the first low energy event, the least amount of variation in ammonia nitrogen concentration from high to low tide was at sites 1 and O1. Site 1 is the furthest away from the outlet and is the most riverine, and site O1 is the closest to the outlet. If there was a tidal influence, it is expected that site O1 would have the greatest variability, and site 1 would have the least variability in the concentration of ammonia nitrogen from high to low tide. Some of the other nutrients such as nitrate + nitrite nitrogen in the first low energy event showed the expected trend, but since this was not evident for all of the nutrients in both of the low energy events, it is concluded that the tide does not affect the concentration of nutrients in this hapua in low energy conditions.

It is likely that tides would influence the concentration of nutrients during storm events. This is because tides play a significant role during sea storms in facilitating wave overtopping at higher tidal stages (Hart, 1999). However, since samples were not taken at different stages of the tide during a storm, this conclusion cannot be supported.

6.6 Limitations and errors

Due to the dynamic nature of the environment and the safety concerns during high energy conditions, samples were not always able to be taken from each of the five sites, however during the flood event the location of the outlet and the shape of the hapua allowed for a sample to be taken close to site O.

While a larger sample size would have increased the accuracy of the results, this was limited by financial constraints. It is possible that the concentration of nutrients varied across the hapua and throughout the vertical profile. Samples could not be taken across the hapua because of the swift flow and the water depth. To account of the possible variation throughout the water column, samples were taken halfway between the hapua bottom and the water surface.

6.7 Summary

This chapter presented the results of nutrient concentrations in different areas of the hapua, in three different energy conditions, and at different stages of the tide. This allowed for the baseline conditions to be determined and how nutrients in this hapua respond to external and internal processes. The water quality was the least healthy in flood conditions, as most nutrient concentrations exceeded the guideline values. The water quality during the storm and low energy conditions was good as none of the nutrient concentrations exceeded the guideline values.

The shape of the hapua has varying influences on the concentration of nutrients. Spatial variation is the greatest during floods. Areas that were isolated from the main current of the river had much lower concentrations. This demonstrates that the flow of the river and the shape of the hapua can have an influence on the concentration of nutrients especially during flood conditions.

Spatial differences usually did not occur in the low energy and storm events. Spatial differences can occur during low energy conditions if wind driven circulation causes fine sediment on the hapua bottom to be stirred up. This is especially evident for total phosphorus and dissolved reactive phosphorus. This study did not investigate how long the effect of wind driven circulation persists for.

Although it is possible that there is an influence of the backwater effect on the concentration of nutrients at different stages of the tide, the influence is deemed to be minimal in comparison to the shape of the hapua, wind driven circulation, and the flow of the river.

Chapter 7: Short-term and long-term hapua geomorphology and behaviour

7.1 Introduction

Both short-term changes and long-term changes in the hapua area, morphology, and behaviour must be understood in order to understand the natural variability and vulnerability of hapua. This must be known for the impacts of any changes in the river hydrological regime on the morphology and subsequent water quality and biota to be adequately predicted and understood.

This chapter presents the methods, results, and interpretation and discussion of changes in the Hurunui River hapua morphology over different time scales. Firstly, hourly images from two time lapse cameras situated at the opposite ends of the hapua aim to qualitatively document the short-term changes in morphology and behaviour of the Hurunui River hapua. Secondly, the quantitative analysis of aerial photographs in *ArcMap 10* from five survey years spanning a time period of 31 years is presented. The aim of this is to document historical changes in the hapua area, shoreline position, the position of the lagoonward side of the barrier shoreline, and the width of the barrier.

The objective of this chapter is to understand natural short-term and long-term cycles in hapua area and behaviour.

This chapter is divided into methods in section 7.2, results in section 7.3, an interpretation and discussion of results in section 7.4, and a summary in section 7.5. The first three sections are divided into two subsections for short-term changes in hapua area and behaviour, and historical changes in hapua area and shoreline.

7.2 Methods

7.2.1 Principles and practices

7.2.1.1 Short-term changes in hapua area and behaviour

Short-term changes in the shoreline position, hapua area, and hapua behaviour can be measured both qualitatively and quantitatively by a number of methods. Accurate short-term changes are typically assessed using global positioning systems (GPS) and LiDAR (Light Detection and Ranging) (Pajak & Leatherman, 2002; Purkis & Klemas, 2011; Schwartz, 2005). The mapping of shorelines using LiDAR is expensive compared to other ground base methods that use equipment such as GPS (Purkis & Klemas, 2011). Measuring the wetted waterline with a GPS is a relatively new method that is cheaper, but can be complicated if the environment is dynamic due to factors such as: wind, tides, waves, river discharge, and beach changes (Kench *et al.,* 2009; Pajak & Leatherman, 2002; Schwartz, 2005; Yang, 2009). Compared to beaches along open coastlines where wetted waterlines are often measured, lagoon environments are less likely to be affected by these factors. When assessing the position of a shoreline, changes in water level must be considered to ensure that any change in the position of the shoreline is not incorrect (Yang, 2009). Time-lapse cameras can also be useful for qualitatively assessing short-term changes, and these have been used in combination with GPS measurements of the wetted water line in previous studies (Pajak & Leatherman, 2002).

7.2.1.2 Historical changes in hapua area and shoreline

Long-term changes in hapua are typically assessed using historical topographical maps and aerial photographs (Pajak & Leatherman, 2002; Purkis & Klemas, 2011; Schwartz, 2005). Aerial photographs are useful for assessing long-term changes in shorelines as well as the rate of any changes, and are a typical method for analysing morphological changes in gravel beaches and barriers (Kokot *et al.,* 2005; Schwartz, 2005).

Area measurements cannot be taken directly from unprocessed aerial photographs due to distortion and displacement in the image (Paine & Kiser, 2012). These inaccuracies result from topographic displacement, tilt, and camera lens distortion when the image was taken

(Paine & Kiser, 2012; Schwartz, 2005; Verhoeven *et al.,* 2012). The image must first be processed to eliminate these distortions. This is done by georeferencing using ground control points. Either control points are taken in the field and the coordinates matched with the same permanent feature in the aerial photograph, or permanent features in the aerial photograph are matched with corresponding control points on an ortho-rectified image of the same site (Paine & Kiser, 2012; Schwartz, 2005). The greatest accuracy is achieved when there are at least 3, well spaced control points per image (Paine & Kiser, 2012; Schwartz, 2005), although more points are normally used to increase accuracy. After georeferencing, an orthorectified image is produced. Each subsequent aerial photograph must be orthorectified to remove the distortions. From the orthorectified image, a planimetric map may be constructed from which area measurements can be taken from (Paine & Kiser, 2012).

When measuring the shoreline, various indicators can be used since the 'true' shoreline is dynamic and constantly changing in response to influences such as waves and tides (Boak & Turner, 2005). Boak and Turner (2005) identifies 45 different shoreline indicators, including the: vegetation line, storm/debris line, erosion scarp, or the wet/dry line.

7.2.2 Data collection and analysis

7.2.2.1 Short-term changes in hapua area and behaviour

In this study the time-lapse cameras were used to give an idea of the short-term changes in the hapua area, shape, behaviour, and frequency of events such as wave overtopping. Two time-lapse cameras were used at this study site, one at the southern end of the hapua, and one further along the hapua that captured the northern end (Figure 7.1). Details of their coordinates are in Appendix 8. One was set up on top of the cliff on the south bank of the river at the start of the hapua (Figure 7.2). The camera faced northwards and was set up for approximately 8 months. This enabled the majority of the hapua to be captured, but did not capture the northern end where the outlet was located for the majority of May, June and July. Therefore, a second camera was installed in June to allow for the changes at the northern end of the hapua to be observed. Each camera took one still image every hour and collated these images into a video sequence. This video sequence was then downloaded each time the site was visited.

Figure 7.1: Location of the time-lapse cameras at the Hurunui River hapua marked by a red x.

Figure 7.2: Time-lapse cameras set up at the northern end (left) and the southern end (right) of the hapua. Both face northwards.

At the southern end of the hapua, time-lapse images were captured for 101 days between the months of May and January. At the northern end, images were captured for 111 days from June to January.

The captured time-lapse sequence was downloaded off each camera as often as possible. Since the video contained a number of still frames per second, each video file was imported into *iMovie.* The night sequences were eliminated and the number of frames per second reduced to approximately one still frame per second. The final edited movie was exported into a *Quicktime* file for visual analysis.

7.2.2.2 Historical changes in hapua area and shoreline

To assess long-term changes in hapua area, unorthorectified aerial photograph prints for the years 1974, 1993, and 1995 were obtained from Environment Canterbury and scanned at a resolution of 600 dpi. The photo for 1974 was black and white, and the 1993 and 1995 the photographs were in colour. Details of the aerial photographs are in Appendix 9. Some of the aerial photographs had up to 19 years between the photographs, while others had a much smaller time gap of 2 years. Therefore, it is likely that a number of significant changes occurred between the years.

The scanned images were saved as a tiff file and imported into *ArcMap 10*. A shapefile of the New Zealand coastline and aerial imagery from Bingmap was imported into *ArcMap 10*. The New Zealand coastline was imported first to ensure that the Bingmap imagery was in the correct geographical space and had the NZTM coordinate system. This bingmap was then used as a basemap to georeference each aerial photograph.

Shapefiles were created in *ArcCatalogue* and features including the hapua water area, shoreline, and position of the lagoonward side of the barrier were digitised in *ArcMap 10* using the editor tool. From this, area measurements and visual comparisons were made, especially in relation to the shape of the hapua.

The definition of the upper limit of a river mouth environment defined by the Resource Management Act is:

"one kilometre upstream from the mouth of a river; or the point upstream that is calculated by multiplying the width of the river mouth by 5" (Environment Canterbury, 2005, p. 221).

Instead of using this classification for the start of the hapua, a line of reference using the forestry plantation was used. This was used for consistency between the photographs since the plantation was present in each of the photographs. When creating a polygon of the hapua area, a line was drawn along the row of trees in the plantation above the campground, across the lower part of the river. This was done to ensure a common reference point for the start of the hapua, and for ease of analysis (Figure 7.3). Due to the dynamic nature of this hapua barrier, and the difficulty with identifying the wet/dry line, the breaker line was used as a shoreline indicator when digitising the shoreline.

Figure 7.3: Line drawn from the tree plantation across the river which was used a a reference for the start point of the hapua.

Once the shoreline and the position of the lagoonward side of the barrier had been digitised, their position was measured and the width of the barrier was calculated. This was achieved by using the *ArcMap 10* extension *ET Geowizards*. This function allowed the position of the shoreline and the lagoonward side of the barrier to be measured more accurately compared to the measure tool in *ArcMap 10.* Firstly, a parallel baseline running the length of the hapua was constructed (Figure 7.4). The 'Split polyline' tool was used to divide the baseline into 200 m sections. Determination lines were extended perpendicular from each 200 m point.

Determination line 1 was the furthest south and determination line 11 was the furthest north. The shoreline shapefile, and the lagoonward side of the barrier shapefile was imported into *ArcMap 10*. The 'Split polyline with layer' tool was then used to determine the distance from the baseline to each of the shapefiles along each determination line. The distance to each shapefile was then analysed in *Microsoft Excel*.

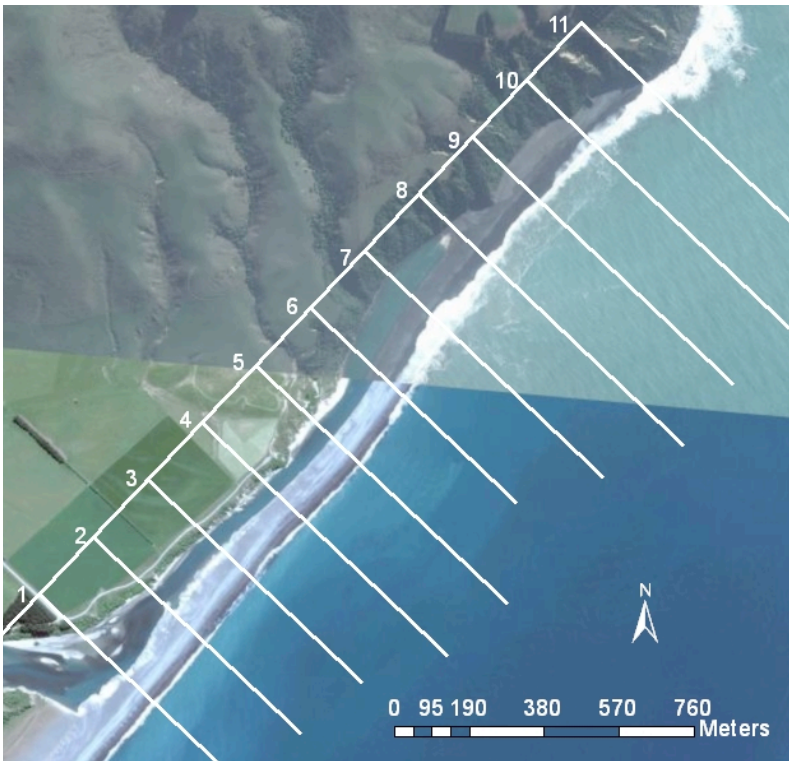


Figure 7.4: Aerial photograph of the Hurunui River hapua overlain with the baseline and determination lines.

7.2.3 Limitations and errors

There were numerous limitations and errors associated with the time-lapse cameras. Firstly, it is possible that there were more overtopping events and flood breaches that occurred but were not counted as they occurred during the night. Also, due to some equipment failures, some days and weeks of images were not recorded. For instance, the northern camera swung around during August and missed 4 days of images. While useful, the time-lapse images were limited to indicative visual observations. As a result, qualitative, not quantitative data was collected.

There were also limitations associated with analysing long-term changes in the hapua from the aerial photographs. Firstly, the georeferencing process and the number of control points were limited because of the small area that was low in elevation across the entire image. The majority of land low in elevation was restricted to areas adjacent to the river. As a result, control points were confined to this area and were unable to be placed to the north and northwest of the hapua. To avoid error associated with the placement of control points, only one person was used to georeference each photograph. Each photograph was limited also by the resolution of each image.

The digitisation of the shoreline of the hapua was affected by a number of factors. Shadows along the backshore of the hapua, especially in the 1993 photograph, introduced inaccuracies with the digitisation. In addition, the influence of the tides on the water level in the hapua would have introduced error, although it is expected that this error would have been within the resolution error of each image for most of the hapua. However, visual observations in the field revealed that significant areas especially near the campground can be covered and uncovered by water between high and low tides. The stage of the tide when the aerial photographs were taken would have had an influence on the total area of the lagoon water body. A margin of error will also always exist when digitising the shoreline due to the constant wave action along the shore.

The amount of change in the shoreline and lagoonward side of the barrier was limited by the pixel size in the aerial photographs and the influence of the tides. Errors associated with pixel size ranged from 1.08 m in the 1993 photograph to 3.4 m in the 2004/2005 image. The change able to be detected in the aerial photographs is limited by the image with the lowest resolution. Since the 2004/2005 image had the largest pixel size, the smallest change that could be detected from the aerial photographs was 3.4m.

Each of the images would have been taken at different stages of the tide (Table 7.1). This would have had an influence on the position of the seaward and lagoonward shorelines. To account for this, a GPS was used to trace the position of the two shorelines at both high and low tide. This allowed for the error in the aerial photographs to be estimated. Taking into consideration both the horizontal and the vertical change, and based on a 95% confidence interval, the average distance that the seaward shoreline moves between the tide and low tide is 8.74 m. Because of the error in the GPS, this measurement can vary by 1.71 m horizontally. The shoreline of the lagoonward side of the barrier moves an average distance of 2.82 m between high and low tide. The error associated with this measurement is 1.33 m. These errors are only an indication since the shoreline was only mapped on one occasion, and the movement of the shoreline depends on the shape of the hapua, as shown in the time lapse images, and the height of the tide. Despite these limitations, valuable information about the change in the position and width of the barrier was obtained.

Table 7.1: Approximate time of high and low tide (during daylight hours) on the day that the aerial images were taken based on the NIWA tide forecaster. The tide times correspond to Lyttelton. The tide at the Hurunui River mouth is approximately 20 minutes later. (* unknown date, the exact date has not been recorded by LINZ, although was likely to have occurred sometime around Christmas).

Date of aerial photograph	**Time of image capture**	**Approximate high tide (mean level of the sea)**	**Tide height (m)**	**Approximate low tide (mean level of the sea)**	**Tide height (m)**
25/12/1974	2.37 pm	1.52 pm	0.72	7.48 am 8.08 pm	-0.66 -0.83
02/07/1993	Not recorded	3 pm	1.06	8.37 am	-1.07
03/09/1995	12.16pm	10.47 am	0.99	5.01 pm	-0.89
2002/2003*	Not recorded				
2004/2005*	Not recorded				

Aerial photographs represent a snapshot in time. It is possible for the hapua area, barrier position and width, and outlet location to change significantly over a short period of time. For more a more accurate analysis, more aerial photographs would need to be analysed. These photographs should be spaced evenly over time, especially over the seasons.

To determine the maximum and minimum amount of change in the shoreline position that could occur from high to low tide, the shoreline would need to be measured at both spring and neap tides. There will always be errors associated with the measurement of the high water line due to meteorological factors (Parker, 2003).

7.3 Results

7.3.1 Short-term changes in hapua area and behaviour

At the northern end of the hapua there were 15 overtopping events over the 137 days of image capture (Tables 7.2 and 7.3). At the southern end, there were 5 overtopping events over the 104 days of image capture. Wave topping of the barrier is more frequent at the northern end of the hapua. Overtopping occurs approximately once every 9 days at the northern end of the hapua, compared to once every 21 days at the southern end. Determining the number of flood events that occurred over the period of image capture by visual observations from the footage was difficult. Therefore, flow data from the State Highway 1 site on the Hurunui River was more reliable in determining the number of floods. Based on a flood threshold of the median daily flow multiplied by 3, the flood threshold over the period of image capture was 213.4m^3/s. There were 14 days that had a daily mean flow over this value. However, some of these days were grouped together so would have been in the same flood event. Therefore, there were 9 flood events from the 2nd of May to the 7th of November 2012. Out of the three main energy conditions, (low energy, floods, and storms), low energy conditions are the most common.

Table 7.2: Frequency of overtopping events and length of camera deployment at different ends of the Hurunui hapua.

Camera location	**Number of overtopping events**	**Number of days of deployment**	**Overtopping events: Length of deployment**
Southern end of hapua	5	104	1:21
Northern end of hapua	15	137	1:9

Table 7.3: Details of when wave overtopping events occurred at the Hurunui River hapua and the maximum significant wave height recorded at the Canterbury wave buoy (data sourced from Environment Canterbury).

Date of overtopping event	**Maximum significant wave height (m)**
2 May 2012	4.41
19 May	5.20
13 June	5.97
15 June	5.92
28 June	8.06
30 June	3.72
1 July	2.96
4 July	2.28
7 August	2.43
8 August	2.88
9 August	2.96
10 August	2.00
15 August	4.59
16 August	3.44
7 October	5.29
14 October	5.23
17 October	3.77
20 October	2.83
7 November	3.22

Over the recording period, observations and changes in the hapua were observed in a range of different energy conditions, with the greatest changes typically occurring in the vicinity of the outlet. When the outlet was at the southern end of the hapua, there was a minimal amount of variation in the area and shape at the northern end. The only visible change was in the slight rise and fall in the lagoon water in response to the tide. During low flow conditions, the tidal influence was evident in the regular covering and uncovering of gravel. At high tide there was little gravel exposed (Figure 7.5), but at low tide there was a significant area of exposed gravel (Figure 7.6). This was most evident at the southern end of the hapua, when the outlet was also at this end. In response to the tide, the water level in the main part of the lagoon fell significantly when the outlet was at the southern end, leading to a large area of gravel being uncovered and causing this area to be temporarily cut off from the main river channel (Figure 7.7). At high tide, the backwater effect of the tide caused the water to flow back into the lagoon, the water level to rise, and the main section of the hapua to be connected to the river channel once again.

Floods also had an influence on the shape and area of the hapua. After a flood, a bank was cut into the landward side of the barrier, although this was more pronounced at the northern end of the hapua barrier (Figure 7.8). This flood bank was then levelled out by waves washing over the barrier during sea storms. Sometimes during smaller floods, the barrier become very narrow but did not breach (Figure 7.9). Ponding on the lagoon side of the barrier sometimes occurred which suggests areas lower in elevation. Floods of considerable magnitude were needed to beach the barrier at the southern end of the hapua. The time lapse images did not capture when the primary flood induced breach occurred, but flow records suggest that a primary breach of the barrier occurred during this study on the 2nd of August 2012 when the mean daily flow was 535.6 m^3/s. For the majority of the floods that had a mean daily flows up to 241.3 m^3/s, the outlet remained at the northern end of the hapua. The outlet only changed to the southern end when a flood of considerable magnitude occurred. When the outlet was located at the northern end of the hapua, there was a change in shape of the barrier after a flood. Before the flood the barrier was relatively straight (Figure 7.10), however after the flood it was more 's' shaped (Figure 7.11), reducing the area of the barrier.

During sea storms, waves sometimes overtopped the barrier. In some storms, the barrier become virtually engulfed by waves and water but did not result in barrier breaching or collapse (Figure 7.12). After wave overtopping of the barrier, the barrier was relatively flat and uniform in elevation (Figure 7.13). The barrier increased in width after each wave overtopping event. On the 7th of October 2012 when overtopping occurred, the width of the barrier was narrower before the overtopping (Figure 7.14) compared to after the overtopping (Figure 7.15). The change in barrier width is not attributed to the influence of the tide on the level of water in the lagoon as the position of the waterline on the landward side of the hapua was not visibly different. After the overtopping event, the wet patches on the barrier, the jaggedness of the barrier lagoon line, and the over wash fans were more evident (Figure 7.15). There was also more overtopping at the mouth of the hapua where the elevation was lower. Wave overtopping of the barrier was sometimes confined to the vicinity of the outlet.

Figure 7.5: Southern end of the hapua close to high tide with little gravel showing on the 23rd of September 2012 when the mean daily flow was 61.2 m^3/s.

Figure 7.6: Southern end of the hapua close to low tide with exposed gravel on the 23rd of September 2012 when the mean daily flow was 61.2 m^3/s. (note the person to the right of the image for an indication of scale).

Figure 7.7: Southern end of the hapua, with the main part of the hapua ponded and cut off at low tide in the top left of the image on the 22nd of September 2012 when the mean daily flow was 64.1 m^3/s.

Figure 7.8: View looking across the hapua towards the barrier, showing the eroded bank after a flood on the 2nd of August 2012 when the mean daily flow was 535.6 m^3/s.

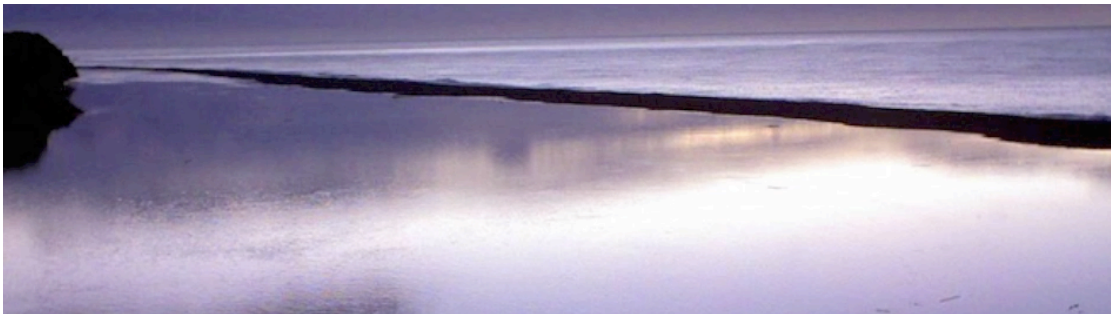


Figure 7.9: Southern end of the hapua during a flood, showing the narrow barrier on the 9th of June 2012 when the mean daily flow was 136.0 m^3/s.

Figure 7.10: Northern end of the hapua just before a flood on the 14th of July 2012 when the mean daily flow was 63.7 m^3/s.

Figure 7.11: Northern end of the hapua during a flood with the visible scarp and storng flow down the main lagoon channel on the 16th of July 2012 when the mean daily flow was 241.3 m^3/s.

Figure 7.12: Southern end of the hapua showing overtopping of waves over the barrier on the 15th of June 2012 when the mean daily flow was 70.4 m^3/s., note the raised water level as evidenced by the water line around the cliff to the left of the image. Significant wave height was 5.92 m.

Figure 7.13: Southern end of the barrier on the 3rd of May 2012 after a storm event, note how the elevation is relatively uniform when the mean daily flow was 39.0 m^3/s.

Figure 7.14: Nothern end of the hapua on the 7th of October 2012 before wave overtopping of the barrier which occurred a few hours later. The mean daily flow was 78.8 m^3/s.

Figure 7.15: northern end of the hapua on the 7th of October 2012 after the storm event on the same day as the image in j, note the difference in the width of the barrier and the visible wave overtopping traces across the barrier. Both the wet patches and the change in barrier lagoon line are more jagged compared to image 7.14. The overwash fans are evident. Significant wave height was 5.29 m.

7.3.2 Historical changes in hapua area and shoreline

7.3.2.1 Hapua water body surface area

The surface area of the Hurunui River hapua water body has varied between the years of 1974 and 2005 (Table 7.4). At this hapua, the difference in area over a few years can be greater than the long-term changes in area. This is because large changes in area are a function of the migration and breaching of the lagoon outlet, the position of which determines the length of the hapua. Over the 31 year aerial photograph record from 1974 to 2005, the water body of the hapua increased by 25,103 m^2, but in the 2 years from 1993 to 1995 there was greater increase of 37,898 m^2. The surface area of the water body of this hapua has also fluctuated in size between the years, with some years greater in size, and others smaller in size compared to the other recorded years. While there has been a slight overall increase in size from 1974 to 2005 (Figure 7.16), short-term changes in the area have occurred and these fluctuations were considerable compared to the long-term change. This demonstrates that although there may appear to be changes in the surface water body area over long time periods, there may in fact be significant changes in the area from year to year as well as during each year.

Table 7.4: Hurunui hapua water body surface area in 5 different years between 1974-2004/2005, and the change in area between the years (+ for increase in size and – for decrease in size), as well as the error (based on the pixel size and change in the position of the shoreline over a tide. Because of the error associated with the GPS, the error can vary up to 1.33 m less than or more than the stated error) * Exact date that the image was taken is not known.

Survey date/photograph	**Years between photographs**	**Hapua area (m^2)**	**Net change since previous image (m^2)**	**Error (m^2)**
25/12/1974		116,158		± 3.92
02/07/1993	19	102,642	-13,516	± 3.92
03/09/1995	2	140,540	+37,898	± 4.22
2002/2003*	9	135,418	-5122	± 5.32
2004/2005*	1 (approximately)	141,261	+5,843	± 6.22

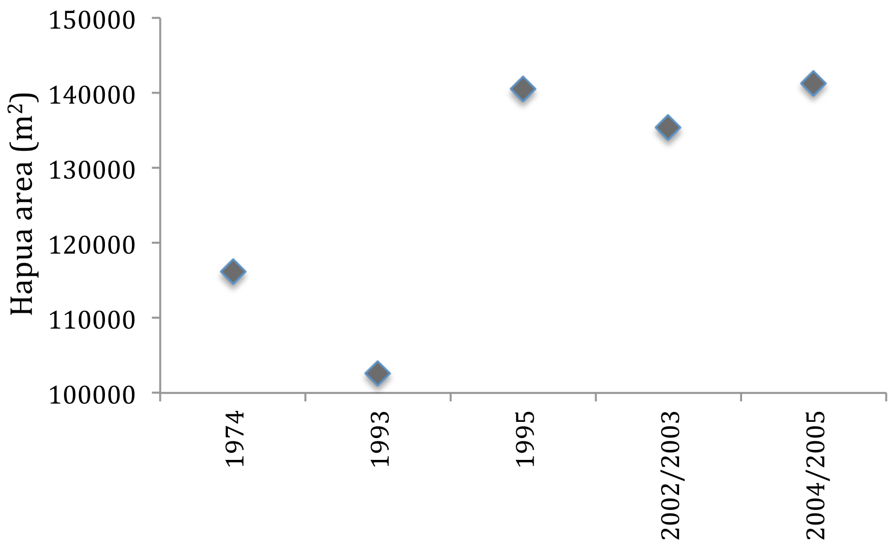
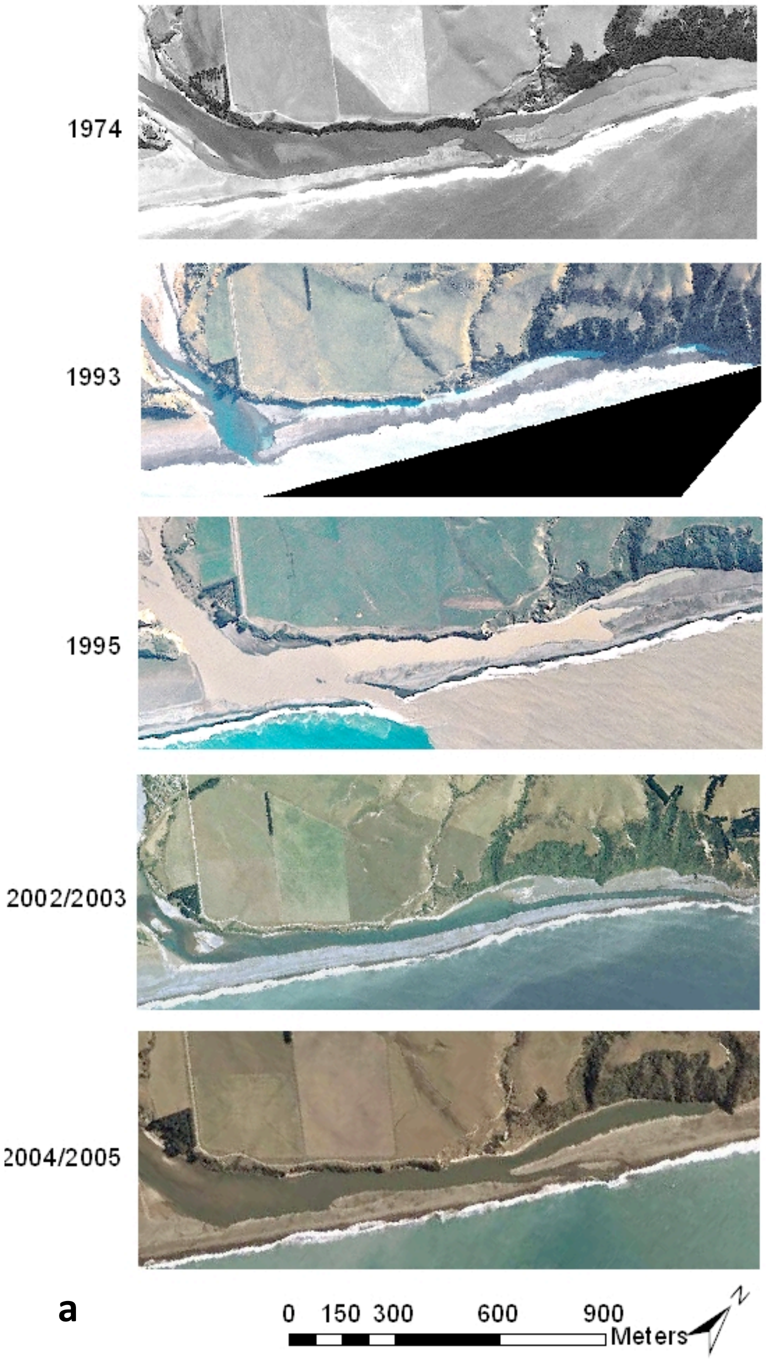


Figure 7.16: Area of the Hurunui River hapua measured from aerial photographs spanning the years 1974 to 2004/2005.

The shape of this hapua from 1974 to 2005 has been variable (Figure 7.17a, 7.17b, and 7.17c). Ponded areas towards the northern end of the hapua have been present in all of the years except for 2002/2003 when the outlet was elongated and extended to the far north of the hapua. The length of the hapua has also been variable, with the northern end of the hapua changing position between each of the years. The location of the outlet has also been variable, with the outlet positioned at the southern end of the hapua in the years 1993 and 1995, and at the northern end in the other three years. It is possible for the outlet to go as far north as the northern extremity of the beach.



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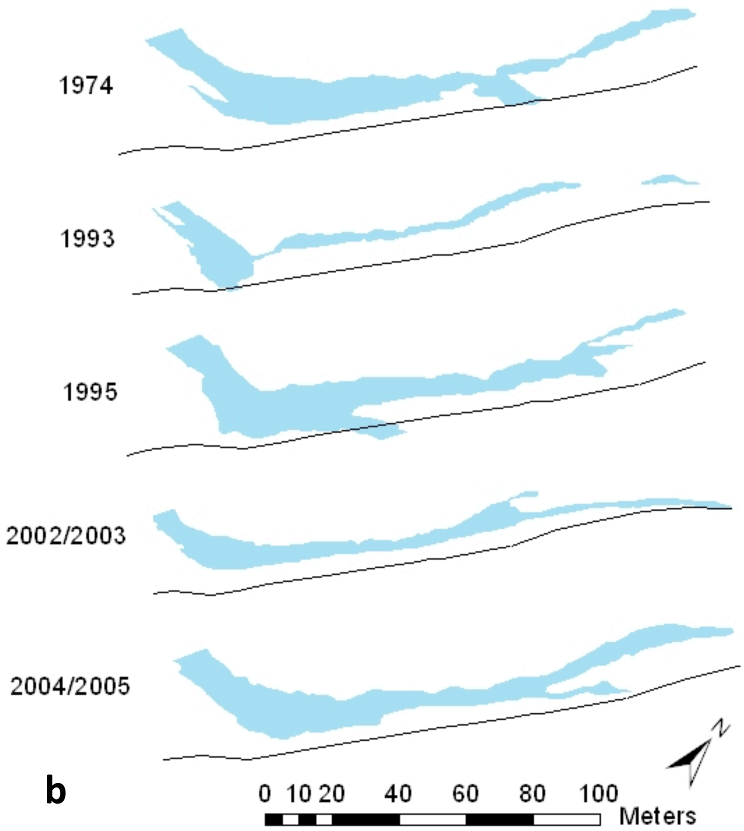

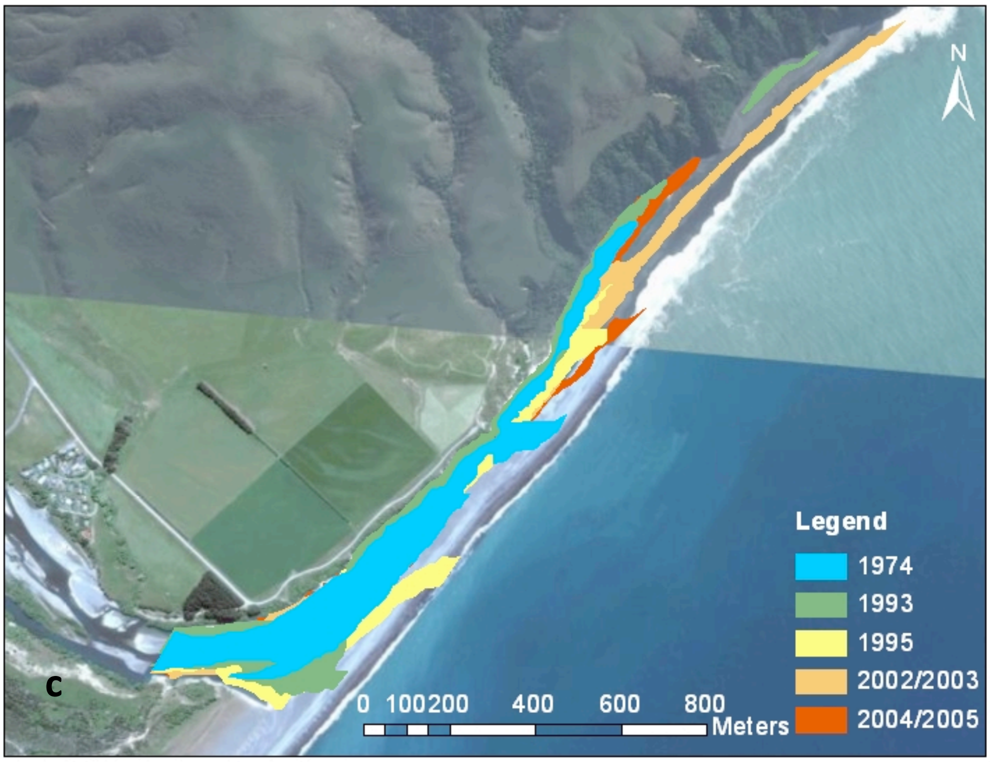

Figure 7.17: Orthorectified aerial photographs of the Hurunui River hapua (a), aerial photograph digitisations of the hapua water surface area (b), and digitisations of the Hurunui River hapua surface water area from aerial photographs spanning 1974 to 2004/2005 (c).

7.3.2.2 Shoreline position and barrier width

The position of the shoreline fluctuated between the 5 recorded years from 1974 to 2004/2005 (Figures 7.18 and 7.19a). From 1974 to 1993 the shoreline moved landward, but then moved seaward from 1993 to 1995. There was a slight overall seaward migration from 1995 to 2002/2003, and the shoreline remained relatively stable from 2002/2003 to 2004/2005. The greatest change in shoreline position occurred around the middle of the hapua, and the smallest amount of change occurred at the southern end. The shoreline position remained relatively stable at the southern end for all of the recorded years except for 1993.

The lagoonward waterline of the barrier also changed position between the years 1974 to 2004/2005, and was more variable compared to the shoreline position (Figures 7.18 and 7.19b). Between baselines 6 and 7, the lagoonward side of the barrier moved landward from 1974 to 1995. From 1995 to 2002/2003 there was a seaward migration, and from 2002/2003 to 2004/2005 the lagoonward side of the barrier moved landward. At the southern end of the hapua, there was a greater change in the position of the lagoonward waterline of the barrier for the recorded years.

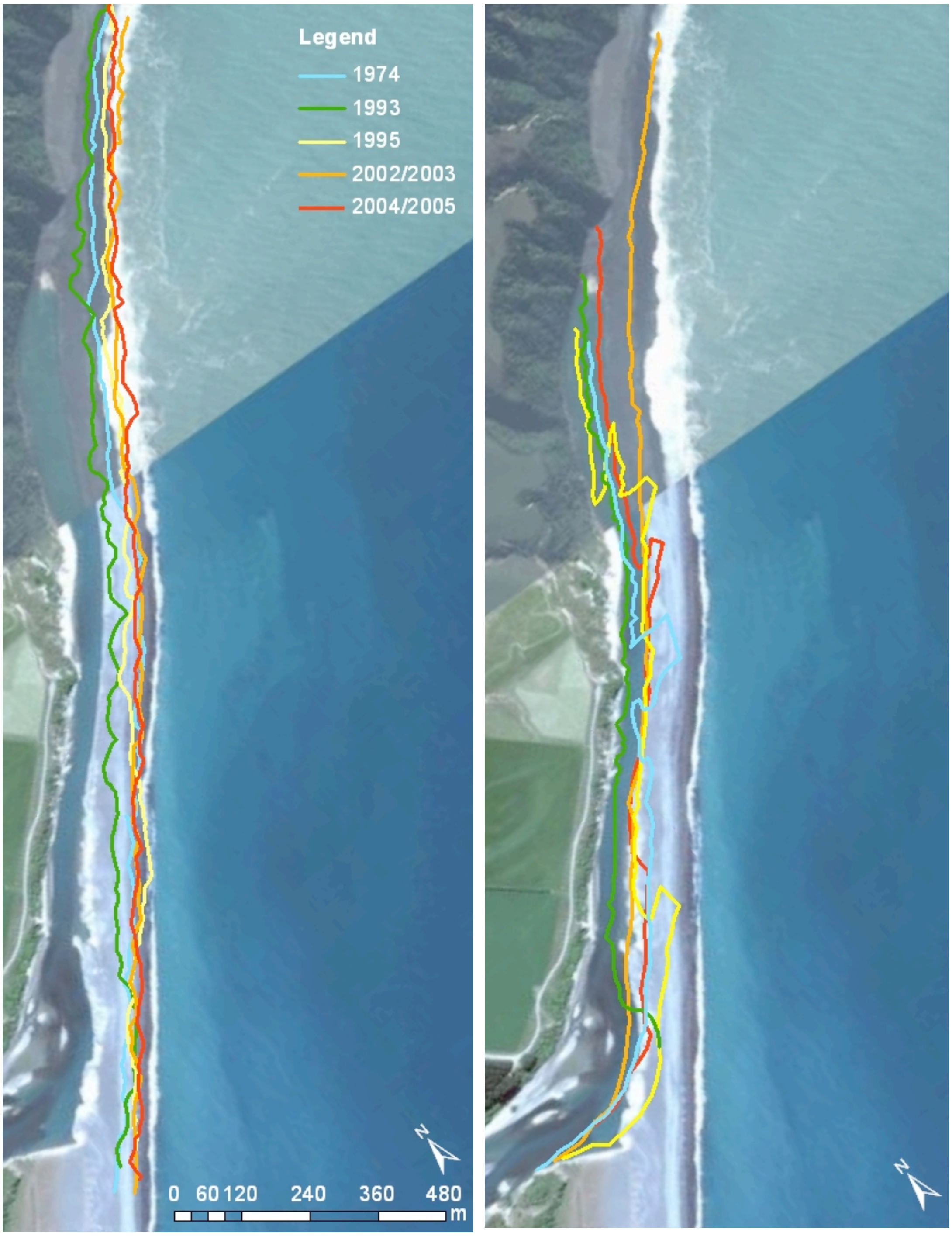

Figure 7.18: Aerial photograph of the Hurunui River hapua with the position of the shoreline (left) and the lagoonward side of the barrier (right) on 5 photographed years from 1974 to 2004/2005. The scale in the left image applies to both images.

The width of the Hurunui hapua barrier was variable both along its length and between the aerial photograph years spanning 1974 to 2004/2005 (Figure 7.19c). The barrier ranged in average width from 65 m in 2002/2003, to 86 m in 2004/2005, although the width was variable along the length of the barrier. 2002/2003 was an exception, with a decreasing width with distance northwards. In this year the barrier was 101 m wide at determination line 1 at the southern end, and 17 m wide at determination line 10 at the northern end. Of all the years, the greatest range in barrier width of 112 m was in 1995, and the smallest range in barrier width of 36 m was in 1993.

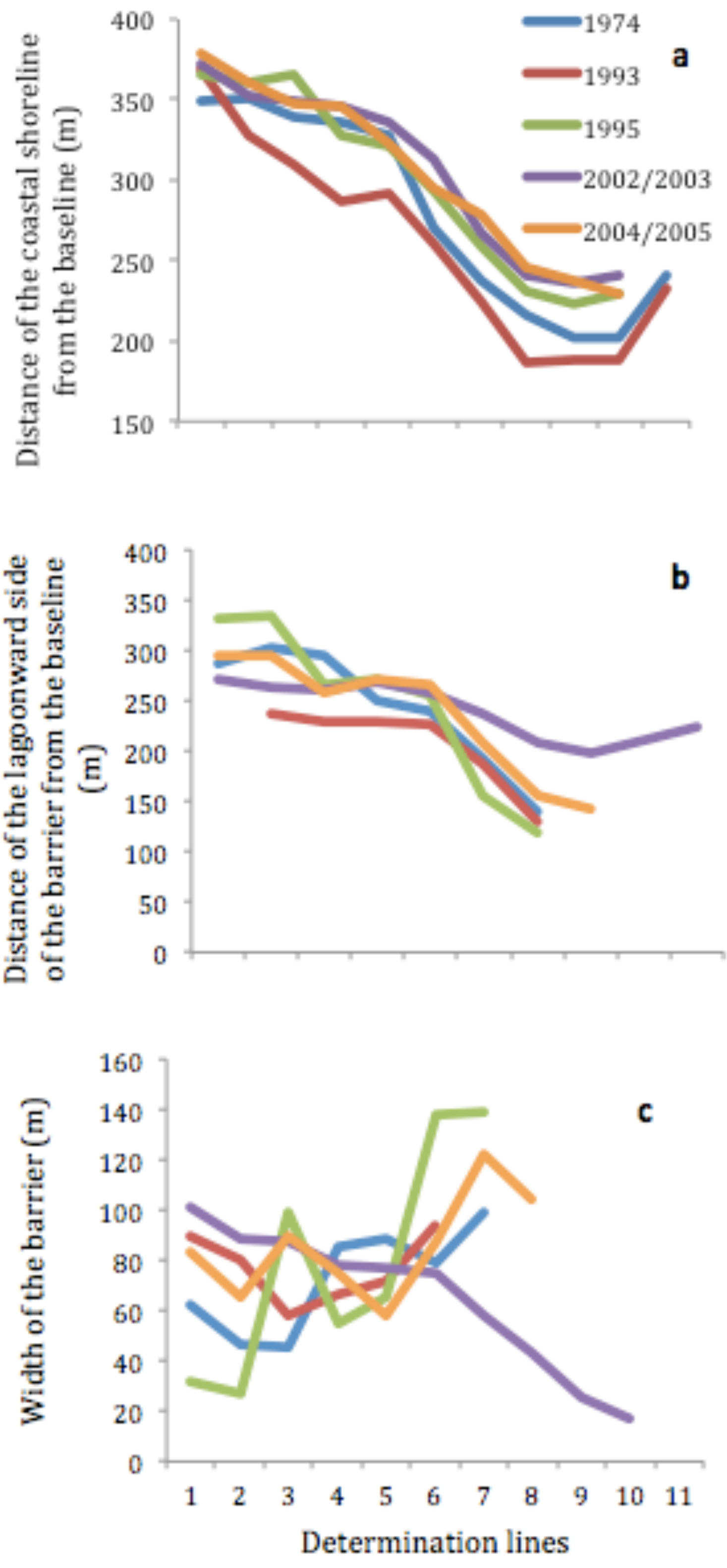

Figure 7.19: Distance of the Hurunui hapua seaward shoreline from the baseline (a), distance of the lagoonward side of the Hurunui hapua from the baseline (b), and width of the Hurunui hapua barrier (c) between 1974 to 2004/2005. Each determination line is spaced at 200 m intervals along the coast from line 1 at the main channel (southern end of the lagoon).

7.4 Interpretation and discussion of results

7.4.1 Short-term changes in hapua area and behaviour

Differences exist in the shape and behaviour at the two ends of this hapua, and this is largely controlled by the position of the outlet and river flow, followed by the indirect influence of the tide on the water level in the lagoon. The greatest changes tend to be in the vicinity of the outlet, especially when it is located at the southern end of the hapua. When this occurs, the greatest changes in the lagoon wetted area happen when the river flow is low. Large areas of gravel are uncovered at low tide compared to high tide (Figures 7.5 and 7.6).

Waves overtopping the barrier during sea storms can result in a breach and pipe failure of the barrier, which is a fairly common occurrence for low lying coarse sediment coastal barriers that do not have dunes (Hart, 2007; Nicholas, 2003). As waves wash over the barrier during storm events, the water level in the lagoon rises and the hydraulic head between the lagoon and the sea rapidly increases as the tide falls. As a result, pipe failure of the porous sediments in the barrier can occur, forming a new outlet (Hart, 2007). Coastal lagoon barrier breaches can also occur due to floods (Hart, 2007; Kjerfve, 1994). Over-topping induced barrier breaching from lagoon to the sea can occur in some hapua such as the Ashburton River hapua (Hart, 2007). However, it is unlikely that this occurs at the Hurunui River hapua. Despite overtopping of the barrier by waves and a rise in water level equal to the top of the barrier, no wave induced breaches occurred over the period that the time-lapse cameras were used (Figure 7.12). Instead, only flood-induced breaches occurred. This suggests that fluvial processes, rather than wave overtopping during sea storms primarily control pipe failure and breach of the barrier at this hapua. The barrier appears to be relatively resistant to flood breaching and will only breach when the river flow is significant. The Hurunui River hapua is likely to be more similar to the Rakaia River hapua that is more controlled by fluvial processes, compared to the Ashburton River hapua that is more driven by waves (Kirk, 1991). While barrier breaching can be a cause for concern especially if there is a significant change in the tidal prism in the coastal lagoon, it is unlikely that this would occur at the Hurunui River hapua due to the flow of the river.

The behaviour of barrier breaching at the Hurunui River hapua can be explained to an extent by the sediment composition of the barrier. This barrier has finer sediment, with more sand in the mixed sand and gravel mix, compared to the Ashburton and Rakaia hapua barriers. Pipe failure of the barrier requires a very porous, permeable layer of sediment (Hart, 1999), so the sediment composition at the Hurunui River hapua explains its resistance to breaching.

During storms when waves wash over a barrier, sediment is moved landwards (Carter & Orford, 1984). It is thought that 10% of the sediment on the crest of hapua barriers is shifted to the landward side of the barrier or washed into the lagoon (Kirk, 1991). A common result of this wash over is a breakdown of the barrier crest (Figure 7.13). The greater the intensity of the storm, the more overtopping there will be and the greater the decrease in elevation of the barrier (Orford *et al.,* 1991). This also results in a marine sediment wash over fans (Orford & Carter, 1982), which was evident after storm events at this site (Figure 7.15).

The reduction in the elevation of the barrier was evident after wave overtopping events and also in the reduction of the flood cut bank on the landward side of the barrier (Figure 7.13). The decrease in elevation of the barrier in the location of an old outlet increased the chance of further wave overtopping. While storms have been identified in increasing the height of the beach crest on coarse barriers, wave over-washing of the barrier can also be important for reducing the crest height (Carter & Orford, 1984; Orford *et al.,* 1991). As a result, the balance between the two processes controls onshore migration of the barrier, and this balance is likely to be altered if there is a change in the rate of sea level rise (Orford *et al.,* 1991). This demonstrates that hapua systems can act as both a source and a sink for sediment depending on the dominating influence, whether it be fluvial or coastal (Kirk, 1983).

Fluvial processes are important in maintaining hapua area and an open and efficient outlet (Hart, 2009b). The importance of floods for carving out space in the hapua was evident as a bank was cut into the lagoonward side of the barrier after a number of flood events (Figure 7.8). While Kirk (1991) initially proposed that small floods were important in reducing the likelihood of outlet closure by maintaining the position of the outlet closer to the main river channel, more recent studies of the Ashburton River hapua have shown that small floods can in fact increase the chance of lagoon closure (Hart, 2007). This is because the outlet migrates further away from the main river channel in small floods, thereby reducing the efficiency of river outflow (Hart, 2007). This scenario is likely for the Hurunui River mouth as the outlet did not appear to migrate southwards during small floods. The northward migration of the outlet during floods at the Hurunui River hapua is constrained by the cliffs to the north located at the southern end of Manuka Bay.

Kirk (1991) stated that the outlet of hapua rapidly displace following a flood breach of the barrier. During this study, a flood-induced breach of the barrier occurred adjacent to the main river channel, but the position of the mouth did not appear to rapidly migrate. While the outlet initially moved southward in response to the wave climate, and then migrated northward again to be aligned with the main river channel, the position of the outlet remained relatively stable over a period of five months.

For most of the time that the images were taken, there was only one outlet, and occasionally there was a short-term secondary flood induced breach. This secondary outlet usually closed within 3 to 4 days. Wave overtopping of the barrier was more prevalent in areas where the outlet was previously located due to lowering of the barrier crest and the lower barrier elevation.

7.4.2 Historical changes in hapua area and shoreline

The lagoon water surface area, shape, and position of the outlet at the Hurunui river hapua over the 31 years from 1974 to 2004/2005 have been highly variable. A greater change in the size of the hapua can be observed from the two aerial photographs from the 1993 to 1995 compared to the difference between the 1974 and 2004/2005 images. Of all the years, 1974 and 1993 had the smallest lagoon surface area. Although the water surface area of the hapua appears to be unrelated to the position of the outlet, the width of the hapua, and the position of the lagoonward side of the barrier, this may be a function of the small number of aerial photographs. The variability in the water surface area of the hapua is also difficult to explain in relation to the location of the outlet and the shape of the hapua because of the limited number of photographs. Hapua are dynamic and can rapidly change in shape and area (D. E. Hart, 2007), therefore the results represent a snapshot, rather than an overall change in surface water area over the 31 years. To obtain an accurate idea about trends and relationships in the water surface area, many more photographs would need to be analysed.

Although the record of aerial images in this study is insufficient to adequately study the relationship between the surface area of hapua and the position of the outlet, Kirk (1983) suggests that there is a relationship. Mouth deflection can result in a reduction in surface area of the lagoon (Kirk, 1983). Of all the photographs, the most northward location of the Hurunui River hapua outlet occurred in 2002/2003. However, the area was not the greatest, nor the smallest of all the photographs. Although the images from this study do not follow the suggestion by Kirk (1983), it is possible that there is a relationship between the position of the mouth and the area of the hapua. To determine whether this is the case, more aerial photographs would need to be interpreted.

The influence of the width of the barrier on the surface water area of the Hurunui River hapua is difficult to determine due to the range of other interacting factors. In 1995 when the mean barrier width was the greatest, the river was in flood at the time of the image capture, hence the largest hapua surface area. For the other years, there is no relationship between the surface area of the hapua and the width of the barrier. Observations from the time-lapse images also showed that the width of the barrier can change significantly before and after a storm event where waves wash over the barrier.

In a study of the Rakaia River hapua, there was a decrease in the surface area from 1952 to 1966, and from 1966 to 2004 the surface area remained stable (McHaffie, 2010). The trend in surface area was attributed mainly to the flow conditions at the time of the image capture (McHaffie, 2010). As identified above, it is also likely that the flow of the river has a major influence on the surface area of the Hurunui River hapua. However, in contrast to the Rakaia hapua that remained relatively stable in surface area from 1952 to 2004, the Hurunui River hapua has fluctuated in area from 1974 to 2004/2005 and has had an overall slight increase in area over this time period. The Hurunui River hapua, like all hapua, experiences a range of shapes in response to the relative influence from both fluvial and coastal processes (Hart, 2009b). The influence of river flow on the area of the hapua is evident when comparing 1995 and 1993. The difference in hapua area between the years is likely to be a reflection of the dynamic nature of the hapua rather than a major overall change in the area of the hapua over the 31 years. Because of this, it is difficult to make comparisons between the years with regard to the area of the hapua. Although it may appear that there has been a change in the area over the long-term, there may in fact be greater fluctuations in the area from year to year.

Accurate conclusions from the analysis of long term changes from aerial photographs is difficult due to the sometimes large changes that can occur over a number of hours at this hapua. The images from the short-term time-lapse camera showed that there can be large changes in the surface area of the Hurunui River hapua over a tide (refer to Figures 7.5 and 7.6). The analysis of the change in area of hapua over time is complicated by the behaviour of mixed sand and gravel beaches. These environments typically remain relatively stable over longer time periods but are punctuated by short rapid periods of change (Forbes *et al.,* 1995), which does occur at the Hurunui River hapua as shown in the time-lapse images. Depending on when the photographs were taken, the lagoon could have been in a relatively stable state, or alternatively, in a short-term period of rapid change. As a result, the area calculation obtained from a single aerial photograph may be an under or over-estimate. Visual observation of the 1995 photograph identified that the river was in flood, however in the other years the river was not in flood. This would have had an influence on the area of the lagoon at the time that the photograph was taken.

Because of these difficulties, the analysis of the change in hapua area over longer time scales must be approached with caution. In order to quantify how much the area changes from high to low tide, especially when the river flow is low and when the outlet is at the southern end, the area would need to be measured at both high and low tide. This would allow for the potential error from the aerial photographs to be estimated.

At the Hurunui River hapua the greatest change, especially in the shoreline position, typically occurred at the northern end from 1974 to 2004/2005. The minimal amount of change at the southern end was likely attributed to the rarity of the outlet occurring at the southern end. Barrier breach at the southern end of the Hurunui hapua adjacent to the main river channel is considered to be rare and may occur less than once a year (Hart, 2009b), or alternatively within any 12 month period (Smith, 1995). As indicated by McHaffie (2010), the river flow and the resulting shape of the Rakaia hapua and location of the outlet may influence the accretion of the backshore. When the river breaches at the southern end of the Rakaia hapua, the low flow in the majority of the hapua may cause backshore accretion as the lower flow prevents scour and erosion. McHaffie (2010) suggests that during outlet migration, the lagoonward side of the barrier is scoured and erosion occurs. In contrast, at the Hurunui hapua in 1993, the outlet was located at the southern end, but the barrier was narrower along the majority of its length compared to the width in 2002/2003. This demonstrates that the width along the barrier of the Hurunui River hapua may respond differently to the Rakaia hapua.

The position of the shoreline and the lagoonward side of the Hurunui River hapua barrier fluctuated from 1974 to 2004/2005. The migration of the lagoonward and seaward side of the barrier did not always follow the same trend. For instance, from 2002/2003 to 2004/2005 the shoreline remained relatively stable, but the lagoonward side migrated landward. In contrast, McHaffie (2010) showed that the Rakaia hapua barrier moved seaward between 1952 and 2004, although the barrier in the five recorded years fluctuated in its position. This demonstrates that over short time scales, such as those used in both of these studies, it is typical of hapua barriers to fluctuate between seaward and landward migration.

Over geological time, it is likely that the barriers of hapua will respond to the movement of the coastline. Kirk (1991) suggested that hapua along the Canterbury Bight such as the Rakaia will move landward in the presence of the current erosion of the wider Canterbury Bight shoreline. The cliffs along this coastline are composed of weakly consolidated sand and gravel from outwash fans that are very erodible. As a result, hapua along this eroding coast will move landward over geological time, especially in the presence of sea level rise. Compared to the net coastal erosion rate of 1 to 2 m yr^{-1} along the Canterbury Bight (Kirk, 1991), the coastline in the Hurunui District is retreating approximately 0.2 m per year (Environment Canterbury, 2005). The shoreline between Napenape (approximately 4.5 km along the coast south of the Hurunui River mouth) and Gore Bay (approximately 5.5 km along the coast north of the Hurunui River mouth) is thought to be in a quasi-stable state (Hicks, 2012). Unlike the shoreline of the hapua along the Canterbury Bight, the Hurunui River hapua has limestone cliffs along its backshore that are less erodible (Lewis *et al.,* 1979). This will have implications for the persistence of the Hurunui River hapua over geological time. Because of the current state of this shoreline, and the composition of the cliffs along the backshore, the Hurunui River hapua is likely to be less vulnerable to landward retreat compared to those situated along the Canterbury Bight.

While the sediment supply and long-term morphological changes in some coastal lagoons can be influenced by tides (Carter & Woodroffe, 1994; Kokot *et al.,* 2005), this is also not the case for hapua type lagoons (Kirk, 1991). Fluvial and marine processes are the major influences on the width and position of hapua barriers (Hart, 2009b). The time lapse images showed that the width of the Hurunui River barrier can change significantly over a storm event. Studies of other coastal lagoons demonstrates that there are many other processes such as climate and sea level rise that will contribute to the evolutionary processes of coastal lagoons (Carter & Woodroffe, 1994; Forbes *et al.,* 1995) (Figure 7.20). Although difficult to quantify, these influences must not be ignored.

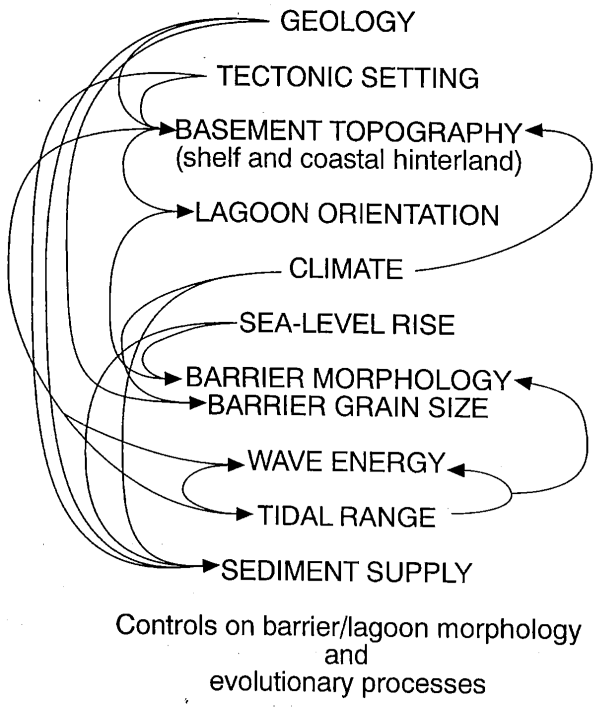

Figure 7.20: Interacting processes which control the evolution of coastal lagoons with associated coarse-grained barriers (Carter & Woodroffe, 1994, p. 247).

7.5 Summary

This chapter has presented the results of both short-term and long-term changes in the Hurunui River hapua. Short-term changes were qualitatively analysed from hourly images taken at the two ends of the hapua spanning a number of months during 2012. Long-term changes in the hapua area, barrier and shoreline position, and barrier width were quantitatively analysed from aerial images from 1974 to 2004/2005. The short-term images were valuable in helping to interpret the changes in the aerial photographs. It is recommended that time lapse images be used in future hapua research.

Analysis of the hourly images allowed for the frequency of events such as wave overtopping to be determined, as well as behaviour and morphological changes in both the lagoon surface area and barrier during periods of low flow, wave overtopping, and floods, and at different stages of the tide. The greatest changes in the morphology, and the highest incidence of wave overtopping occurred in the vicinity of the outlet. Pipe failure and breaching of the barrier at the Hurunui River hapua only occurs during large floods, and does not typically breach due to the rise in lagoon water level associated with wave overtopping. The change in surface area in response to the tide is more prevalent when the outlet is located at the southern end of the hapua.

Analysis of previous river flow data in Chapter 3 showed that the greatest flows occur in September and October. Analysis of wave data in Chapter 3 also showed that waves with a significant wave height 1 to 2.5 m were the most common, but waves up to 5 m can occur. Since the time-lapse cameras were deployed for approximately 7 months, the response of the hapua to high energy events was able to be reasonably well observed.

While there has been an overall increase in the hapua area from 1974 to 2004/2005, there have been fluctuations from year to year. A greater observed change in the area occurred over the 2 years from 1993 to 1995 compared to the change over the past 31 years. There have also been fluctuations in the position of the barrier shoreline and lagoonward position, as well as the width of the barrier. The greatest change in the shoreline position occurred at the northern end of the hapua compared to the southern end. The width of the barrier appears to be related to the relative influence of marine and fluvial processes. For most of the time the barrier width is variable along its length. However when flows are moderate to low, and marine processes dominate, the outlet migrates to the northern end and becomes elongated. This results in a decrease in the barrier width in the northward direction.

The area and position and width of the barrier of this hapua is dynamic over both short and long time scales. While there may be changes over the long-term, greater changes can occur over shorter time periods.

Chapter 8: Integrated discussion

8.1 Introduction

The previous five chapters have presented the results from this research. First, the river flow and water quality in the lower Hurunui River, and the significant wave and direction over the approximately last 10 years was presented. Next, the results of the current baseline water quality characteristics and sediment processes in the Hurunui River hapua were presented. The short-term and long-term characteristics in the geomorphology and behaviour of the hapua were also presented. Each of these chapters provided an interpretation and discussion of the findings.

This chapter is articulated around two objectives. This includes an assessment of the contemporary health of the Hurunui hapua, and an assessment of the influence that different energy conditions have on the hapua geomorphology and characteristics of the lagoon water body. This chapter also aims to assess the vulnerability of this system to continued catchment pressures, in particular, dams. This research does not assess the actual effects of dam projects on the Hurunui River hapua since dams are still in the proposal stage. Rather, it provides the needed baseline information, previously unavailable, that will be essential for future research to assess the impacts of any dams after they are built. The need to assess and collect this baseline data has not been met by any other study.

The knowledge of the current state of the Hurunui hapua as assessed in this thesis, and the review on how dams affect river and, thus, the inputs to the rivermouth environment, will be used to assess the potential impacts of the Hurunui and Waitohi River dam proposals on the Hurunui River mouth. Specifically, these predictions are in response to the change in hydrological regime and sediment processes associated with the dams. The potential impacts discussed will focus on the geomorphology of the hapua, sediment processes (both suspended and deposited sediment), water quality (chemical and physical water quality parameters), and biota. Suggested management considerations and the remaining gaps in the knowledge will also be discussed.

This chapter will address the overall aim of examining the current conditions and the long-term geomorphology at the Hurunui River hapua, and the potential impacts of the proposed dam developments on the Hurunui River hapua. The objectives include:

- to determine the overall current health of the Hurunui River hapua and any controls on the water quality;
- to predict the impacts that could occur on the hapua geomorphology, water quality, sediment processes, and biota if there is a change in the hydrological regime and sediment processes; and
- to discuss management options for the Hurunui River hapua.

8.2 Current hapua health

The health of coastal lagoons can be based on a range of parameters including: aquatic vegetation; turbidity; water quality variables such as conductivity, dissolved oxygen and nutrients; sediment; ecological characteristics; toxicants such as metals and aromatic hydrocarbons; and microbiological parameters (Environment Canterbury, 2011a; Hernández-Romero *et al.,* 2004; Newton *et al.,* 2003; Pereira *et al.,* 2009; Scanes *et al.,* 2007). The present health of the Hurunui River hapua is based on the following parameters in relation to the guideline values: conductivity, dissolved oxygen, pH, total nitrogen, ammonia nitrogen, nitrate + nitrite nitrogen, total phosphorus, and dissolved reactive phosphorus.

Based on the period during this study, in its present state the health of the Hurunui River hapua is considered to be good. This is based on low energy conditions since they are the most common. In this state, most of the parameters are within the guidelines (Table 8.1). The health of the hapua is also good during storms. Although conductivity is high, the health is still considered to be good since the elevated conductivity is short in duration. The health of the hapua is poor during floods, but this is also short in duration.

It is likely that the health of the hapua can be poor in low energy conditions, especially during late summer and early autumn when river flows are at their lowest. Toxic algae and prolific algae growth can occur during low and stable river flow at the State Highway 1 site on the Hurunui River (Environment Canterbury, 2012b). This indicates that the health in the hapua can also be poor during these periods.

Table 8.1: Parameters that exceeded or were within the ANZECC & ARMCANZ (2000) guidelines during the three energy conditions (* refers to the water quality standards for coastal lakes and lagoons in the Canterbury Region set by Environment Canterbury (2011a), ** refers to the typical range for conductivity in Canterbury Rivers (Hayward, 2003), and *** refers to the guideline based on the 75th percentile (Ausseil, 2010)). √ refers to a mean value within the guideline, and X to a mean outside of the guideline.

Parameter	**Guideline**	**Low energy**	**Floods**	**Storms**
Conductivity	50-250 uS/cm**	√ when outlet is at the northern end, X when the outlet is at the southern end	√ when outlet is at the northern end, X when the outlet is at the southern end	X
Dissolved oxygen	6 mg/L	√	√	√
pH	7.5-8.8***	√	√	√
Total nitrogen	0.614 mg/L 0.34 mg/L*	√ X	X	√
Ammonia nitrogen	0.9 mg/L	√	√	√
Nitrate + nitrite nitrogen	0.444 mg/L	√	√	√
Total phosphorus	0.02 mg/L*	√	X	√
Dissolved reactive phosphorus	0.01 mg/L	√	X	√

8.2.1 Water quality states

Distinct water quality zones have been identified in coastal lagoons based on salinity and nutrient concentrations (Herrera, 1994). Coastal lagoons have also been characterised in terms of water quality based on conductivity because it is a useful indicator of the amount of freshwater and seawater influence (Lucena *et al.,* 2002). Different water quality states (Figure 8.1) exist in the Hurunui River hapua. These states depend on the relationship of the geomorphology and position of the outlet with the water quality parameters, and the concentration of nutrients and suspended sediment. Although spatial trends are more significant, and water quality is generally poorer during floods and sea storms, the following states are based on low energy conditions. This is because low energy conditions are the most common and high energy events are temporary and less frequent. Some of the parameters indicate that some areas were better in water quality compared to other areas of the hapua, but other parameters indicated the opposite. Therefore, the following states are based on the strongest trends.

The first state is when the outlet is located at the northern end of the hapua, no ponded areas are present, and flow is relatively uniform along its entire length. In this state, it is considered that the water quality throughout the hapua is the same, and the best in quality. This is because spatial differences did not appear to be evident when the outlet was at the northern end of the hapua for water temperature, conductivity, dissolved oxygen, and all of the nutrients (Tables 8.2 and 8.3). The only exception was pH, and this was probably due to the eroding limestone cliff about halfway along the hapua. The absence of ponded areas in this state ensures that most of the hapua experiences a reasonable flow and a small residence time of water.

When the outlet is at the southern end of the hapua, water quality is likely to be poorer compared to when the outlet is at the northern end. When the outlet is at the southern end, ponded areas are present, and spatial variations for some of the water quality parameters exist. Conductivity and pH in this state varied spatially, while water temperature, dissolved oxygen, and suspended sediment did not vary. This higher conductivity was due to waves that had washed over the barrier, and taken a long time to flush out of the ponded area. This caused the water in the ponded area to be poorer in quality compared to the unponded areas. Nutrient concentrations also varied spatially when the outlet was at the southern end of the hapua (Table 8.3), but this was likely due to the resuspension of fine sediment from the bottom of the hapua as a result of wind driven circulation of the water column, rather than the geomorphology and position of the outlet. The water quality in the ponded area in this state depends on how much the backwater effect of the tide influences mixing of the water. It is possible that water quality would decline in the ponded area in flows lower than those during the sampling period, as less water would flow into the ponded area at high tide.

The intermediate water quality state occurs when the outlet is at the northern end, and some ponded areas are present. There is the potential for water quality to be poorer in the ponded areas, compared to those that are close to the main current of the river. In particular, conductivity and temperature are likely to be higher in the ponded area where the water residence time is greater.

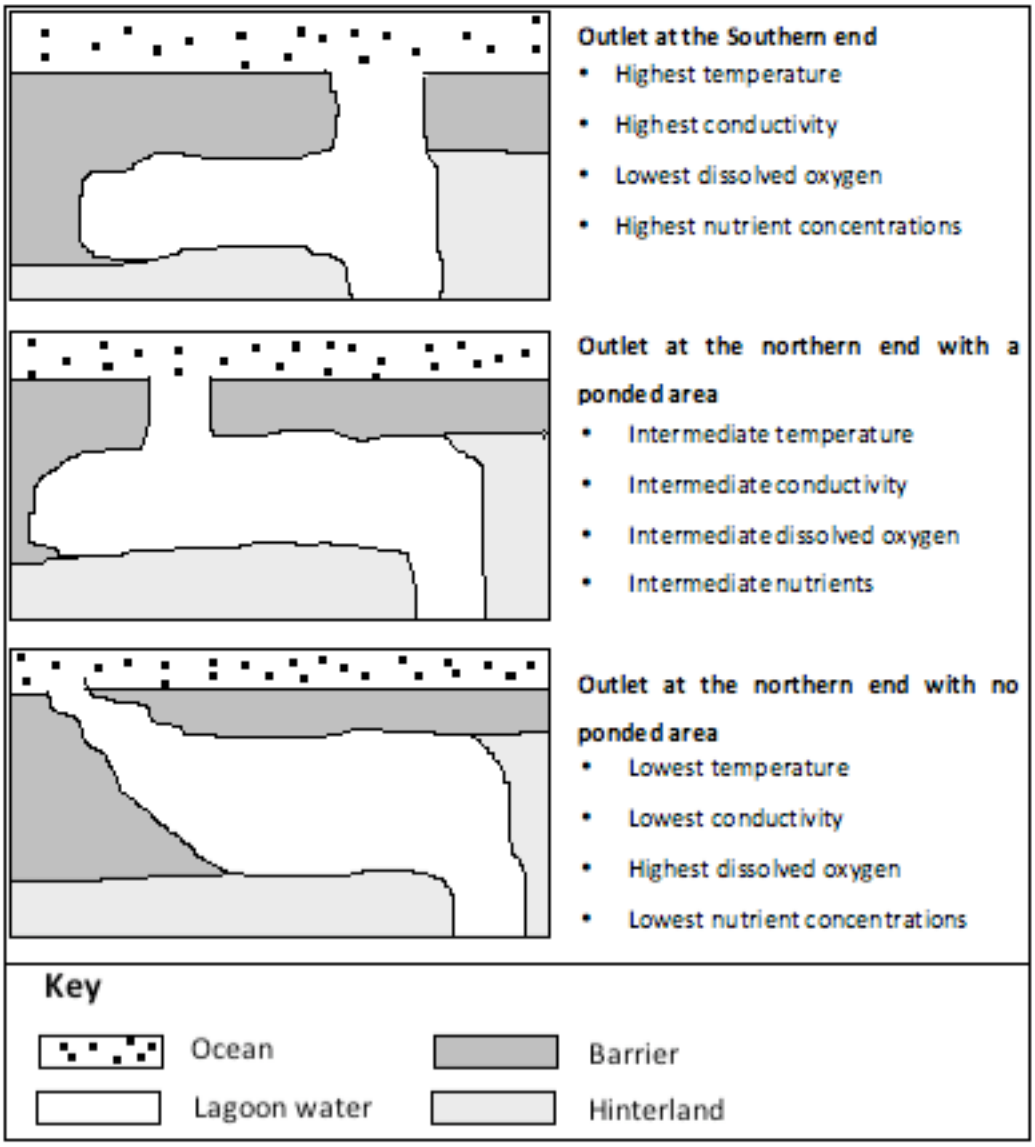

Figure 8.1: Typical states that can exist at the Hurunui River hapua, with the characteristic differences in parameters that vary the most with the different morphology.

Table 8.2: The influence of outlet position and energy event on spatial trends in water quality parameters and suspended sediment (√ spatial differences, X no spatial differences, - not tested for, * the spatial differences in suspended sediment were much greater in the flood conditions when the outlet was located at the southern end compared to the northern end.

		Water temperature	Conductivity	Dissolved oxygen	pH	Suspended sediment
Outlet at southern end	Low energy	X	√	X	√	X
	Flood	√	√	√	√	√*
	Storm	√	√	√	√	√
Outlet at northern end	Low energy	X	X	X	√	X
	Flood	X	X	X	√	√
	Storm	-	-	-	-	-

Table 8.3: The influence of outlet position and energy event on spatial trends in total nitrogen (TN), ammonia nitrogen (AN), nitrate + nitrite nitrogen (NNN), total phosphorus (TP), dissolved reactive phosphorus (DRP) (√ spatial variation in nutrient concentration, X no spatial variation in nutrient concentration, * parameter affected by wind driven resuspension of fine sediment from the hapua bottom during the time of sampling). Numbers correspond to the highest mean concentration in the different events, the higher the number the greater the mean concentration.

	TN	**AN**	**NNN**	**TP**	**DRP**
Low energy with the outlet to the north (no ponded areas)	X, 2	X, 3	X, 3	X, 1	X, 1
Low energy with the outlet to the south (ponded areas present)	X, 3	X, 2	X, 4	√, 3*	√, 2*
Flood	√, 4	√, 4	√, 2	√, 4	√, 4
Storm	X, 1	X, 1	√, 1	X, 2	X, 3

Deviations from these water quality states could occur due to other external influences other than floods and storms. Water quality in the Hurunui River hapua can change in response to wind. The concentration of total phosphorus and dissolved reactive phosphorus do not vary spatially in low energy conditions, but variation can occur if wind causes fine sediment on the hapua bottom to be suspended. This results in a temporary decrease in water quality as these nutrients increase in concentration and turbidity is elevated. Even though nutrients did not vary spatially when the outlet was at the northern end, the results from the low energy event when the outlet was at the southern end demonstrates that variation can occur if there is a strong wind. This demonstrates that water quality can be additionally by water circulation within the hapua.

8.3 Identified changes that could occur post dam

As highlighted in Chapter 1, there are currently two main proposals for irrigation development in the Hurunui District. These proposals involve the Hurunui and Waitohi Rivers (Hurunui District Council & Canterbury Water, 2010; Waitohi Selection Panel, 2011).

Information is limited on how these dam developments could impact the Hurunui River mouth. While the potential impacts on the geomorphology and behaviour of the hapua have been predicted, the potential impacts on the health of the waterway and biota have been largely ignored. To develop predictions of the possible impacts at the river mouth, the current conditions, behaviour of the hapua, and pre-existing cycles of change must be known and understood. Baseline information is of utmost importance for any potential impacts to be assessed. Geomorphological changes at the river mouth are especially important to understand as these can have a major control on ecosystem ecology (Ligon *et al.,* 1995).

8.3.1 Hydrological regime

Predictions have been made on how the hydrological regime of the Hurunui River would most likely be altered if either of the dam proposals were to occur. Elsewhere, dam and water developments have resulted in variable alterations to the flow regime of New Zealand rivers. While some such as the Waiau River in Southland have had a decrease in baseflow, others such as the Waikato River have had an increase (Young *et al.,* 2004).

It is thought that the major changes to the Hurunui River hydrological regime under the Hurunui River proposal would be: a reduction in flow variability during most of the year, higher base flows and more variability during the summer months, and a reduction in flood frequency and magnitude (Figure 8.2) (Christensen & Torgerson, 2012; Lin, 2009; Ward & Veendrick, 2009). It is expected that the proposed Waitohi River dams would reduce flood flows and reduce the number of floods greater than the mean annual flood by 10%.

However, a proposed sediment-flushing regime is expected to allow floods 300 m^3/s to still occur and move down the Waitohi River during the winter (Christensen & Torgerson, 2012). It is likely that there would be a slight reduction in the flood frequency, flood magnitude, and baseflows, but a minimal impact on higher flows in the Hurunui River under the Waitohi River proposal (Veendrick *et al.,* 2012). Baseflows at the Hurunui River mouth are expected to reduce under both of the proposals due to the combined effects of the dams and water abstraction for irrigation (Christensen & Torgerson, 2012; Lin, 2009; Mosley & Environment Canterbury, 2004).

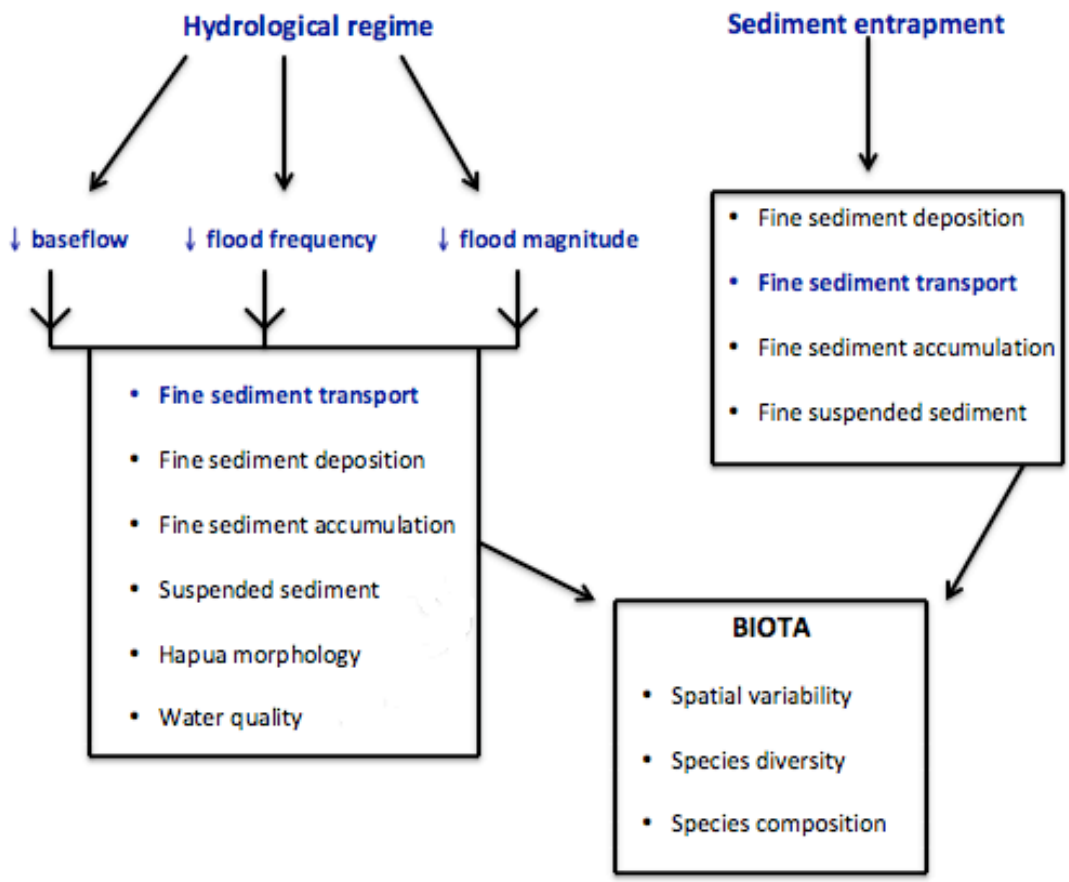

Figure 8.2: Summary of the effects that the change in hydrological regime and sediment entrapment post dam could have on the hapua. Text in blue refers to the effects that have already been identified as being likely to occur.

8.3.2 Sediment transport

Sediment transport is likely to be altered by the dams (Christensen & Torgerson, 2012). There are differing opinions on how the sediment transport would be altered under both of the proposals. While suspended sediment under both proposals is likely to reduce, it is expected that the impacts would be mitigated somewhat under the Waitohi River proposal due to a sediment-flushing regime incorporated into the intakes (Christensen & Torgerson, 2012; Environment Canterbury, 2011g). Suspended sediment is expected to reduce by 13% in the Hurunui River downstream of the Waitohi River confluence if the Waitohi dams and water diversion from the Hurunui River is approved, although this percentage could change depending on the efficiency of the sediment-flushing regime. The flow in the Hurunui River is expected to decrease, reducing the transport of sediment downstream (Christensen & Torgerson, 2012).

Although it has been identified that the transport of suspended sediment to the river mouth is likely to reduce if the Waitohi or Hurunui River developments are to occur (Christensen & Torgerson, 2012), the effects of the potential changes on the hapua are unknown.

8.4 Potential impacts at the hapua from the change in hydrological regime

There are numerous difficulties with studying hapua type coastal lagoons. The majority of studies on coastal lagoons have been on lagoons with stable morphology and finer sediments (Comin *et al.,* 1991; Herrera, 1994; Jones *et al.,* 2003; Lucena *et al.,* 2002; Pereira *et al.,* 2009), unlike hapua that are located on mixed sand and gravel coastlines which can experience rapid morphological changes. Because of this dynamic nature, difficulties are introduced when examining spatial trends in suspended sediment, nutrients, and physical and chemical water quality parameters. Predicting how changes in the river catchment could impact the associated coastal lagoon is also difficult because of the balance between fluvial and coastal influences (Lucena-Moya *et al.,* 2012; Sklar & Browder, 1998).

Potential changes to the river mouth post dam must take into account a range of factors including: external influences such as floods and storms and their relationship with the geomorphology; geomorphology and its relationship with water quality; water quality and its relationship with the ecology; and geomorphology of the system and its vulnerability in the presence of a range of pressures such as sea level rise (Figure 8.3). From this study, it is clear that these aspects are interrelated. Spatial trends and the concentration of a range of physical and chemical water quality parameters in this hapua depend on both the river flow and coastal influences, and more importantly, the geomorphology of the hapua.

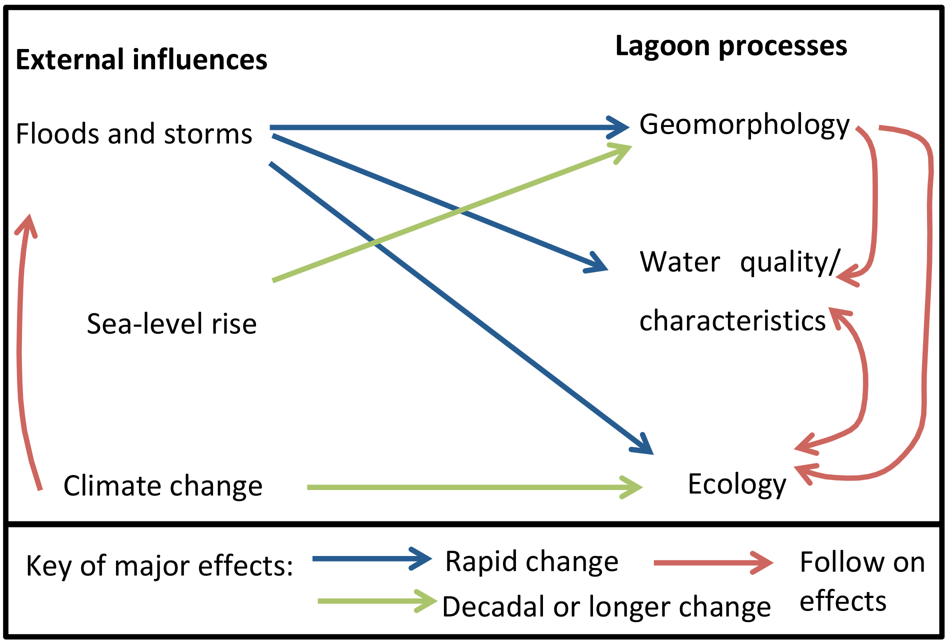

Figure 8.3: Conceptual diagram of external influences on hapua, the effect on internal processes, and any follow on effects. Rapid change is based on changes over hours or days.

The following potential impacts on the Hurunui hapua in response to the described scenarios are speculative based on the collected baseline information from this study, and from case studies in the literature. Without this baseline information, impacts would be difficult to make post dam development.

8.4.1 Hapua geomorphology

The geomorphology of hapua is intricately related to fluvial and marine processes (Hart, 2007), and the geology of the area. Any change in either of these will have implications for the geomorphology of the hapua. It is highly likely that the shape of the hapua would change with the predicted reduction in river baseflow, and alteration to the frequency and magnitude of floods. From this study, additional information specific to the geomorphology and behaviour of the Hurunui River hapua was gained. From this, predictions with regard to the potential changes post dam are made.

During periods of low river flow when sea conditions are moderate, or when both river and sea conditions are low in energy, marine processes dominate hapua systems (Hart, 2009a, 2009b; Kirk, 1983). When this occurs, longshore drift causes the outlet to migrate northwards, and floods of significant magnitude are needed for a primary breach to occur (Hart, 2009b). The time-lapse images did not capture the moment when the primary flood induced breach at the Hurunui River hapua. However, flow records plus photos either side of the event indicate that a primary breach of the barrier occurred on the 2nd of August 2012 when the mean daily flow was 535.6 m^3/s. This barrier was not breached before this event despite a number of smaller floods occurring. These floods had mean daily flows up to 241.3 m^3/s.

Based on mean daily flow from the 1st of January 2002 to the 20th of November 2012, and a flood threshold of 146.1 m^3/s (median flow multiplied by 3), there were 187 days where the mean daily flow was between 146.1 and 241.3 m^3/s at the SH1 site on the Hurunui River. There were only 7 days over this period with floods greater than 535.6 m^3/s. Of the 194 floods that have occurred since the 1st of January 2002, it is likely that only 7 of them have resulted in a primary breach of the Hurunui River hapua barrier. Therefore, it is concluded that primary breaches of the barrier may occur every 1.5 years, although this frequency depends on the flow of the river, the strength of the barrier, and the time of tide (Smith, 1995).

Under the Hurunui River proposal, the change in flood magnitude post dam would cause the outlet to remain at the northern end and possibly eliminate the occurrence of primary breaches of the barrier. Smith (1995) suggested that primary breach of the barrier occurs at flows as low as 400 m^3/s. The exact flow thresholds required for a primary breach to occur under all conditions are unknown. However, it is thought that the outlet would most likely remain at the northern end of the hapua in floods that have a mean daily flow less than or equal to 241.3 m^3/s, and possibly higher. If the hydrological regime under this scenario reduces the flood magnitude below that of the critical threshold for a primary breach, marine dominance would increase and the outlet would remain at the northern end. It has been identified that reduced baseflows can cause hapua outlets to migrate northwards (Hicks, 2012; Kirk, 1983), but so far the effect an altered hydrological regime on primary breach has not been assessed.

Under the Waitohi proposal, the impact of a change in flood magnitude on primary breach of the Hurunui River hapua, and the location of the outlet is likely to remain unaltered. Since the flood regimes in the Hurunui and Waitohi Rivers are likely to remain unaffected, and flows at least 535.6 m^3/s in magnitude still persist, primary breach of the Hurunui River hapua barrier would still occasionally happen. However, the reduction in flood frequency would cause this event to become less frequent.

The geomorphology of the Hurunui River hapua will still respond to floods that are smaller in magnitude. If floods were eliminated completely, and primary breaches no longer occurred, this system would evolve over time. These changes would take a long time to occur, possibly hundreds of years, and it is unknown how the system would respond exactly. However, since floods would still occur post dam, the overall effect on the location of the mouth of the Hurunui River hapua would be the maintenance of the outlet at the northern end.

The greatest impact on the geomorphology of the Hurunui River hapua under the Waitohi proposal would be due to the reduction in baseflows. The outlet would migrate to the northern end as fluvial influence decreases and marine processes dominate. Unlike the Hurunui River proposal, the outlet could be positioned at the southern end of the hapua when primary breaches of the barrier occur. The reduction in baseflows due to irrigation abstractions have been linked to the offset and migrated outlet to the north of the Rakaia River hapua (Kirk, 1983). Like the Rakaia, the northward orientation of the outlet at the Hurunui River hapua may increase the susceptibility of the barrier to breaching. This occurs because of the reduced efficiency of the outlet (Kirk, 1983).

Under the Waitohi River proposal, the irrigation season would be from 1 October to 1 May (Veendrick *et al.,* 2012). Because water would not be taken exclusively from the dam lakes, the post dam hydro pattern would have an irrigation signature. Under this proposal, there would be a marine-dominated summer low flow period. This would cause the outlet to migrate to the north of the Hurunui River hapua as fluvial influence decreases and marine dominance increases.

The reduction in flood magnitude would also confine outlet migration to the northern end under the Hurunui River proposal. The outlet of hapua typically circulates through a cycle of positions (Paterson *et al.,* 2001) (Figure 8.4). Firstly, a flood will cut an outlet through the barrier adjacent to the river channel (A). Longshore drift will cause the channel to orientate in the direction of longshore transport and the channel to lengthen (B-D). As the efficiency of the outlet channel reduces as a result of channel elongation, a high energy event such as a flood or storm will form new and more efficient outlet to form (E), from which this process begins again (Paterson *et al.,* 2001). If primary outlet breaches no longer occur post dam, steps A to C at the southern end would be eliminated. Steps D to F would still occur but would be localised to the northern end. As a result, the change in flow regime could reduce the area in which outlet migration occurs, limiting the cycle to the northern end of the hapua. Alternatively, outlet migration would remain largely unaffected under the Waitohi River proposal.

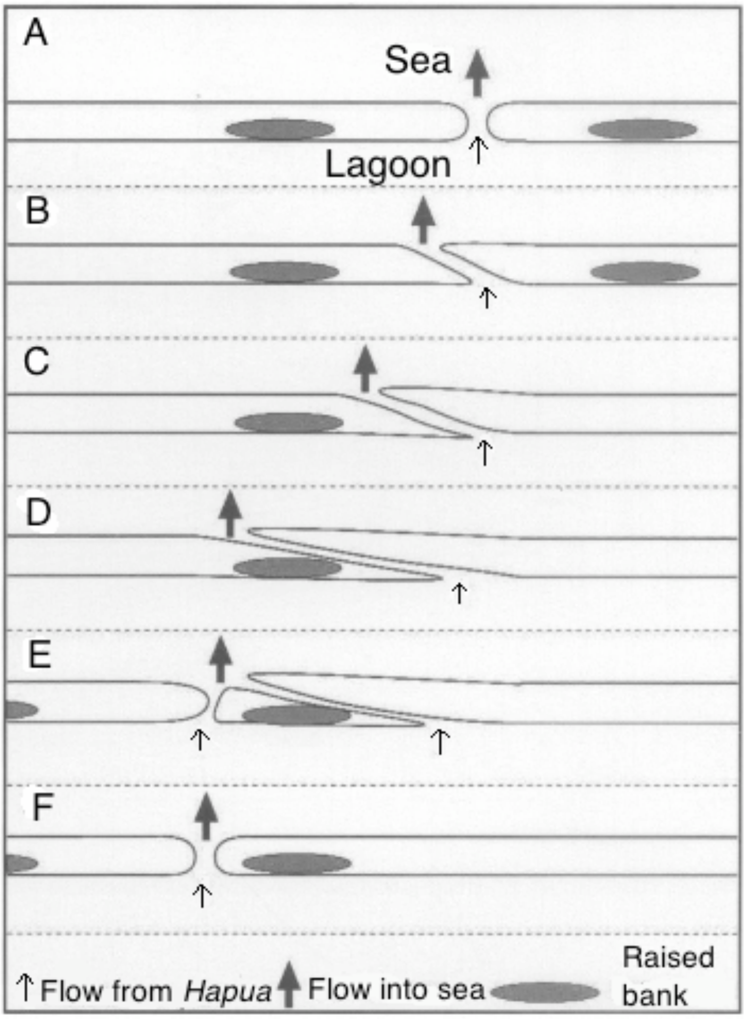

Figure 8.4: Model of the typical outlet migration sequence of hapua (Paterson *et al.,* 2001, p. 292).

As well as reducing the area in which outlet migration occurs under the Hurunui River proposal, maintenance of the outlet at the northern end of the hapua could also reduce the occurrence of outlet migration. At the Ashburton River hapua, the outlet migrates to areas along the barrier lowest in elevation between the berms which are higher in elevation (Paterson *et al.,* 2001). With the elimination of flood induced barrier breach at the southern end of the hapua, and the absence of storm induced barrier breach occurring at this hapua, two potential scenarios could occur. Firstly, the increase in marine dominance could increase the height of the berms along the barrier. This would reduce the number of areas along the barrier that are lower in elevation, thereby reducing outlet migration. Alternatively, these berms would be lowered in elevation during storm events when waves overtop the barrier, possibly allowing for the outlet to migrate more readily along the barrier immediately after the storm. This migration would then be constrained as the berms are built up gain by waves. It is deemed most probable that outlet migration would be limited for most of the time, with short periods of increased migration after storm events when the height of the barrier is lower. Outlet migration would quickly reduce as the berms are built up again by waves.

The maintenance of the outlet at the northern end of the hapua due to the change in hydrological regime would alter the prevalence of ponded areas. Based on observations from this study, ponded areas were less prevalent when the outlet was located at the northern end of the hapua compared to when it was at the southern end. Although ponded areas can occur when the outlet is at the northern end, a larger area is ponded when the outlet is at the southern end. This is because the primary breach results in the majority of the hapua becoming a backwater (Kirk, 1983). It is possible that distinctive ponded areas do occur when the outlet is located at the northern end, as shown in some of the historical aerial images. However, observations from this study indicate that these ponded areas persist for a much shorter time, for days to a few weeks. The ponded area is also smaller in area, compared to the ponded areas when the outlet is at the southern end that can persist for months. Ponded areas may occur more often when the outlet is at the northern end than is currently thought, but since this was not particularly evident during this study, it is concluded that ponded areas are more defined and common when the outlet is located at the southern end of the hapua.

Under the Hurunui River proposal, the change in the outlet position as a result of a post dam change in hydrological regime would alter the short-term variations in surface area in response to the backwater effect of the tide. When the outlet is at the southern end, variations in the surface area are greater between the tides compared to the northern end. It is probable that there would be less variation in the surface area over the tide with the outlet maintained at the northern end. This would have implications for suitable habitat for aquatic species.

The likely northward orientation of the Hurunui River outlet post dam would have a different effect on water quality issues compared to the effects that have been observed at the Rakaia and Ashburton River mouths. The reduction in flow due to water abstraction for irrigation, and the reduction in moderate floods has resulted in the outlets of the Rakaia and Ashburton River hapua being maintained at the northern end of the lagoon (Micallef & Williams, 2009; Single, 2011). In this state, the efficiency of flow is reduced so water can pond and pose a flooding risk to the huts located along the backshore (Hicks, 2012; Micallef & Williams, 2009; Single, 2011). This can also lead to poor water quality due to the longer residence time of water (Micallef & Williams, 2009). In contrast, when the outlet is at the northern end of the Hurunui River hapua, flow is still significant throughout the hapua (Figure 8.5). The difference in flow throughout the Hurunui River hapua can be explained by the sediment composition and porosity of the barrier. The Hurunui hapua is composed of finer sediments, so throughflow is less compared to the Ashburton hapua (Hart, 1999). The estimated subsurface throughflow at the Ashburton hapua barrier is 0.76 to 16.48 cumecs, compared to 1.23 to 12.21 cumecs at the Hurunui hapua (Hart, 1999). As a result, more water is diverted through the Hurunui lagoon, reducing the potential for water quality problems and mouth closure to occur. However, the overall effect of the northward location of the outlet on the water quality in the lagoon would depend on the flow in the river.

Figure 8.5: Outlet of the Hurunui River hapua (looking southwards) when it was located at the northern end of the lagoon. Note the ripples which show the strong flow.

The analysis of historic aerial images suggests that the Hurunui River hapua is increasing in size, although it can fluctuate significantly from year to year. Because of this, it is likely that this system is not currently in a particularly vulnerable state with regard to its persistence over time. This also suggests that the area of this system is not significantly vulnerable to changes in the flow regime of the river resulting from water abstraction for irrigation. Therefore, it is possible that the area of the hapua may not be impacted in the future if there is dam development. With the outlet maintained at the northern end, there could be less fluctuation in the surface water area as a more stable geomorphology is maintained. Overall, it is probable that there would be less fluctuation in the long-term geomorphology involving the hapua area, shoreline position, and barrier width as the fluvial influence decreases due to the change in the river flow regime.

Alternatively, this system could reduce in size as the flood frequency and magnitude is reduced. The time-lapse images showed that floods cut into the barrier. Floods are important in carving out the spaces that are occupied by hapua, and prevent them from infilling (Hart, 2007). Gravel dominated barriers can migrate inland as a result of wave overtopping (Orford *et al.,* 1991). With the expected reduction in flood frequency and magnitude under the Hurunui proposal, the hapua area could reduce as the sediment washed into the hapua from storm events is less readily removed from the lagoon by floods. Unlike hapua situated along the Canterbury Bight that have highly erodible cliffs, the limestone backshore at the Hurunui River hapua is more resistant to erosion (Figure 8.6), so this hapua is likely to have a slower retreat over historical time. The area of the hapua could remain unaffected under the Waitohi proposal because of the smaller reduction in flood magnitude.

Figure 8.6: Backshore of the Ashburton hapua (left) with loosely consolidated cliffs, and the limestone backshore of the Hurunui hapua (right). Ashburton hapua photo courtesy of Deirdre Hart.

8.4.2 Water quality

The position of the outlet and the shape of the hapua are likely to have an influence on the water quality in the Hurunui River hapua. The change in morphology and position of the outlet under the Hurunui River proposal is likely to affect spatial trends in water quality. During this study, spatial trends in suspended sediment, water quality parameters, and nutrients were less evident in both low flow and flood conditions when the outlet was at the northern end of the hapua, compared to when it was located at the southern end. This was because there was less variation in the flow throughout the hapua when the outlet was located at the northern end.

Spatial trends were particularly evident during a flood when the main outlet was at the southern end. During this flood, there was a prominent ponded area, which was part of the previous main channel of the hapua (Figure 8.7). The main outlet was at the southern end of the hapua, and a second smaller outlet remained at the northern end. This ponded area was away from the main current of the river and was distinctive in terms of nutrients, suspended sediment, and water parameters, compared to the rest of the hapua. The conductivity was much higher in this ponded area, 31710 uS/cm, compared to around 80 uS/cm at most of the other sites.

Figure 8.7: View southwards from the northern end of the Hurunui River hapua. The ponded area is at the bottom of the photograph, and the outlet is to the left.

This demonstrates that when the main outlet is at the southern end of the hapua and ponded areas are present, spatial differences are greater. It is concluded that with the predicted northern orientation of the outlet post dam, spatial variation throughout the hapua in suspended sediment, nutrients, and water parameters in would reduce since the flow throughout the hapua would be similar. If ponded areas still occur when the outlet is at the northern end, there would be some variation, especially during floods. Physical and chemical characteristics of the water, and suspended sediment would vary spatially during floods when the outlet is at the southern end. Conductivity is the only parameter that would vary during low energy conditions if ponded areas are present, and would be greater in the ponded areas due to the longer residence time of seawater. It is concluded that major spatial variation would only occur if the hydrological regime allowed for floods of high enough magnitude to maintain an outlet at the southern end. This is likely to occur under the Waitohi proposal, but not the Hurunui River proposal.

With a reduction in baseflow, the location of the outlet at the northern end of the hapua could reduce the chance of water quality problems. In low energy conditions, water temperature and all of the nutrients except for ammonia nitrogen were lower in concentration when the outlet was located at the northern end of the Hurunui hapua. Although river flow, surface and groundwater inputs in the catchment, and other water characteristics would have been different in the two events, the results indicate that water quality is better when the outlet is at the northern end. It is also important to note that water temperature was measured a few months apart, so the results may be a reflection of external influences such as air temperature, rather than the location of the outlet. Despite this, water quality post dam would likely be improved with the outlet maintained at the northern end, although without further investigation and a larger number of samples and events, this conclusion cannot be adequately supported. The results from this study do indicate, however, that these low flow conditions are worth further investigation.

The indication of better water quality with the outlet maintained at the northern end of the Hurunui River hapua is in contrast to the Rakaia River hapua. As discussed above, the reduction in baseflow and the maintenance of the outlet at the northern end has been linked to water quality degradation, a change in water temperature, and limited fish ingress (Kirk, 1991). Approximately 40 years ago the Rakaia hapua had large areas of aquatic macrophytes, as well as a greater fish population compared to its present state (B.Southward, personal communication, February 17, 2013). River flow modification has also been linked to the northward orientation and subsequent water and ecological degradation of the Ashburton hapua (Micallef & Williams, 2009). Like the Rakaia and Ashburton hapua, it is possible that the position of the outlet at the northern end of the Hurunui River hapua could alter water temperature and hence water quality, but the effect is likely to be different. As discussed above, this study indicates that water quality can be better when the outlet is at the northern end since water flow tends to be significant throughout the hapua. Harmful algal blooms can occur in the lower Hurunui River in periods of stable and low river flow (Environment Canterbury, 2012b), so if the baseflows are reduced enough that these growths occur, water quality in the hapua is likely to be compromised.

The hydrological regime and sediment processes are the main drivers of change at the river mouth, but other interacting factors must be taken into account. Since the purpose of the proposed dams is to increase water availability for irrigation and agriculture, it is possible that nutrients and suspended fine sediment in the waterway would increase due to agriculture intensification and greater surface runoff (Clapcott *et al.,* 2011). Freshwater discharge into coastal lagoons can have a major control on the water chemical and physical characteristics, as well as the biology in the lagoon (Comin *et al.,* 1991; Lucena *et al.,* 2002; Sklar & Browder, 1998). With the predicted lower base flows at the river mouth due to water abstraction for irrigation, water quality issues are likely to increase if the water residence time increases. If ponded areas are present, temperature and conductivity could increase, and dissolved oxygen reduce (Alvarez-Borrego & Alvarez-Borrego, 1982). Conductivity especially would increase as the flushing of seawater that enters the hapua from waves washing over the barrier during sea storms would take longer. Alternatively, it is possible that nutrient loadings in the river could reduce if farm management practices improve, which has occurred in the Pahau River (Environment Canterbury, 2011c). In particular, in this example, dissolved reactive phosphorus concentrations in the lower Hurunui River have reduced as a result of efforts to control phosphorus inputs into the river from wipe-off water (Environment Canterbury, 2011c).

Although the quality of the water in the hapua at the time of sampling in this study was within guideline values in the low energy conditions, it is highly likely that there will continue to be a degradation in water quality with changes to the flow regime of the river, and nutrient loadings as a result of agricultural intensification in the river catchment.

The purpose of the dam proposals is to increase the availability of water in the Hurunui District for agriculture irrigation (Canterbury Water *et al.,* 2011; Environment Canterbury, 2011g). Overall, river water in New Zealand is in decline (NIWA, 2012a). Rivers that flow through pastoral land are some of the poorest in water quality in New Zealand (Ballantine *et al.,* 2010; Larned *et al.,* 2004). In the Canterbury Region, spring-fed plains streams and spring-fed lower basin streams are the poorest in quality, although alpine and hill-fed rivers can have poor water in their lower reaches if they flow through farmland (Stevenson *et al.,* 2010). This is due to the runoff of effluent and nutrients such as nitrogen and phosphorus from the land (Ballantine *et al.,* 2010). Despite most of the measured nutrients at the SH1 site on the Hurunui River having not changed significantly in concentration over the past 7.5 years, this river does have a downstream decrease in water quality (Ausseil, 2010). The quality of the water in the hapua at the time of sampling in this study was within guideline values in the low energy conditions. However, it is likely that there will continue to be a degradation in water quality as the river flow regime is altered. Agricultural intensification in the catchment is also likely to increase nutrient concentrations in the river and hapua. Water quality at the river mouth is likely to be compromised and further degraded post dam development if significant measures are not put in place to reduce nutrient inputs into the Hurunui River and its tributaries. Although the poorest water quality in terms of nutrients, especially phosphorus, was during the short-term floods, it is likely that the water quality in low energy conditions would also decline in the Hurunui River hapua.

The influence of climate change must also be taken into account when evaluating post dam impacts on the Hurunui River hapua. The predicted increase in air temperature in the region and greater rainfall in the Hurunui River headwaters could have varying impacts on the river hydrology (Lin, 2009; Ward & Veendrick, 2009). Flows could increase due to the predicted increase in rainfall at the headwaters of the Hurunui River, although flows in the lower river could reduce in response to greater air temperatures and increased water abstraction for irrigation (Mullan *et al.,* 2008). If climate change results in reduced flows at the river mouth, the maintained position of the river mouth to the northern end, and the resulting geomorphology would likely reduce variability in water characteristics throughout the hapua.

8.4.3 Sediment processes

If there is a change in suspended sediment in the hapua, other water quality parameters could be altered. As the results show, water temperatures are higher when there is less suspended sediment. If suspended sediment decreases, water temperature in the hapua could increase. This would then alter other water quality parameters that are related to water temperature such as dissolved oxygen. All of these potential changes would then have implications for biota living within the hapua.

The deposition of sediment in the hapua is also likely to be altered by the dam developments. Sediment deposition could either increase or decrease. During this study, it was identified that during smaller floods, such as the flood on the 24th of June 2012 when the mean daily flow was 201.1 m^3/s, a large amount of fine sediment was deposited along the shoreline of the hapua. This sediment was not removed until a flood of significant magnitude with a mean daily flow of 535.6 m^3/s occurred. This demonstrates that significant floods are required to scour away fine sediment that has been deposited along the shore by smaller floods. The majority of fine sediment is transported to the ocean during floods (Kirk, 1983), and while this is evident at the Hurunui River mouth by the defined sediment plume in the ocean during floods, the deposition of fine sediment along the hapua in the falling limb of the flood does occur. If there is a reduction in flood magnitude, the amount of sediment deposited along the shore of the hapua could increase and the hapua would trap more fine sediment, especially on the margins along the backshore of the hapua.

Alternatively, the entrapment of sediment in the dams, as well as the reduction in the carrying capacity and flood frequency of the river could reduce the amount of sediment available to be deposited within the hapua. This is because a reduction in flood frequency or magnitude, or both, can reduce the amount of deep-flushing of fine sediment from the braided riverbed upstream (Hicks, 2012). This would be mitigated to some extent by the sediment-flushing regime that is proposed to be incorporated into the intakes associated with the Waitohi proposal. Because flood frequency under both of the proposals is expected to reduce, fine sediment deposition at the river mouth could decrease. The effect would be the greatest under the Hurunui proposal. The decrease in fine sediment deposition at the river mouth would depend on how much the flood magnitude reduces by, and on how the deep-flushing of sediment from the braids upstream is altered.

Overall, the change in sediment deposition at the hapua post dam is difficult to predict. It is evident that numerous factors have to be taken into account including the change in deep-flushing of sediment from the braided sections upstream, the amount of sediment available to be transported, and the reduction in flood magnitude and frequency. For instance, a reduction in flood magnitude could limit the removal of fine sediment deposited in the hapua by smaller floods, so fine sediment deposition would increase. However, if the flood magnitude reduces below the threshold required for deep-flushing of fine sediment upstream, then sediment deposition could reduce as fine sediment transport reduces.

If there is a change in fine sediment deposition along the shore of the hapua, sediment composition along the backshore of the hapua would likely change. This is more likely to occur under the Hurunui proposal. If fine sediment deposition increases, the composition of sediment would reduce in size. If floods magnitude is reduced below the critical value required to remove the fine sediment that is deposited by smaller floods, the sediment composition would reduce in variability, with most of the sediment being sand and mud. These changes would be limited to the landward side of the hapua shore. A change in sediment composition would be minimal close to the outlet due to the dynamic nature and the constantly shifting outlet in response to the wave environment. The sediment composition would also remain mostly unaffected along the barrier side of the hapua shore due to the influence of waves washing over the barrier during sea storms. Alternatively, the amount of fines along the backshore of the hapua could reduce if there is a reduction in fine sediment deposition. Overall, the affect of the proposed dams on the sediment composition in the Hurunui River hapua would depend on how the change in river flow and flood frequency and magnitude and the subsequent fine sediment transport is altered. Any changes that do occur would have implications for biota.

8.4.4 Biota

With the predicted change in hapua shape, sediment processes and water quality under the proposed dam developments, there would be numerous implications for biota. A range of impacts on river mouth, estuarine and coastal ecosystems have been identified due to alterations in river hydrological regimes worldwide (Figure 8.8) (Sklar & Browder, 1998). The alteration of freshwater inflows into these systems and the effect on the quality and characteristics of the water often have a major influence on the structure and function of biotic communities (Sklar & Browder, 1998). The effects of these changes are complex because of the many feedbacks. Because of the absence of information on how the biota at river mouths have been impacted by dam and water developments in the catchments of rivers in New Zealand, worldwide examples have been identified. An ecological assessment of the Hurunui River hapua was not within the objectives of this study, therefore the following predictions are based on changes that are likely to occur with regard to sediment processes, water characteristics, and geomorphology post dam development.

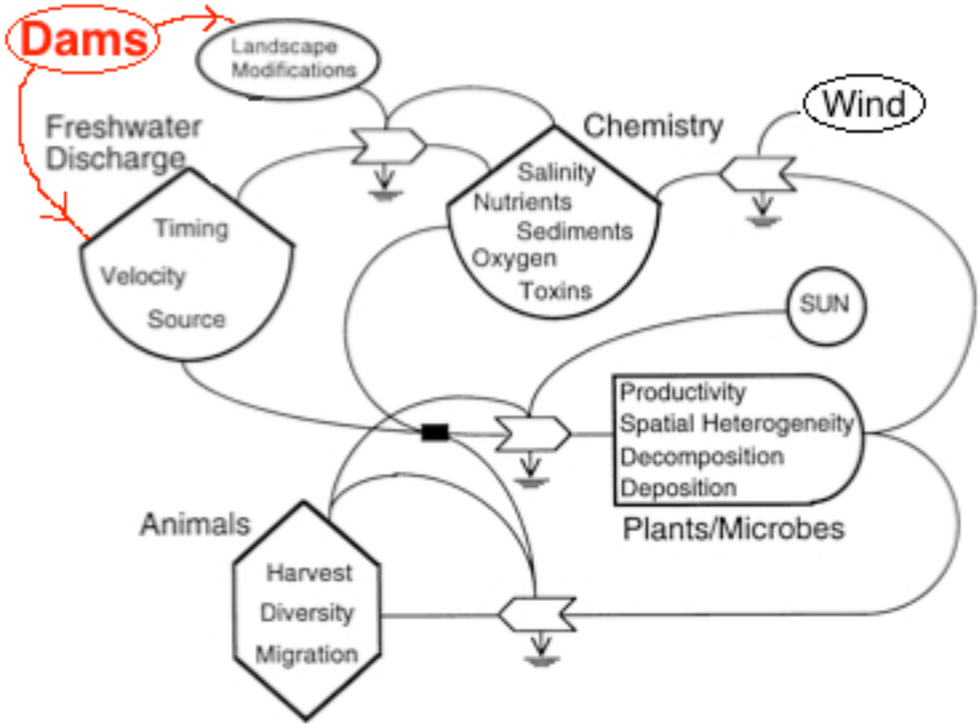

Figure 8.8: A conceptual model of the range of direct and indirect effects that a change in freshwater discharge can have on the chemistry, animals and plants/microbes in coastal lagoons. The arrows correspond to the direction of the influence and the associated additional variables. The diagram has been modified to include wind and dams. The major effect related to this study is labelled in red (Sklar & Browder, 1998, p. 548).

Benthic biota in a Mediterranean coastal lagoon has been impacted by a change in the hydrological regime in the lagoon catchment (Stora & Arnoux, 1983). Dam developments increased the freshwater discharge into the lagoon. As a result, salinity in the coastal lagoon decreased and became more variable, and dissolved oxygen concentration decreased. The change in hydrological regime also caused an increase in sedimentation. The changes in the physical characteristics of the water and sediment resulted in a loss of species (Stora & Arnoux, 1983).

Although the change to the hydrological regime of the Hurunui River is likely to be different and less dramatic, it is likely that biota would also be impacted because of the range of changes involving: sediment processes, water quality parameters, nutrient concentrations, spatial patterns, and short-term and long-term geomorphology. Unlike the biota in the Mediterranean lagoon that have been impacted primarily by a change in salinity (Stora & Arnoux, 1983), the biota in this hapua is likely to alter as a result of a change in substrate stability and a change in the concentration of nutrients and water parameters such as temperature, conductivity, dissolved oxygen, and pH.

Numerous ecological changes could occur in response to the northerly orientation of the outlet post dam. As identified above, spatial variation in the water quality parameters, suspended sediment, and nutrients would probably reduce after the dams are constructed, or if there is a significant reduction in the flood frequency and magnitude. Brackish algae species could be eliminated if there are no longer ponded areas with higher salinity. In its current state, this hapua has distinct 'micro' habitats in terms of substrate composition, water quality parameters such as conductivity, and nutrient concentrations. With the outlet at the northern end, spatial variability could reduce, and these micro-habitats would be eliminated or changed. As a result, species composition and possibly diversity in the Hurunui River hapua would change.

As identified earlier, there is a chance that the stability of the substrate and the composition of sediment could change. The substrate would be more stable if there is a decrease in fine sediment deposition, and the sediment is composed of larger sediments. A more stable substrate would increase the potential for biota such as algae to establish, which would then increase the stability of the sediment even further (Nichols & Boon, 1994). Any change that does occur to the sediment composition would determine the species able to inhabit the area. If there is a reduction in the size of sediment and an increase in fine sediment deposition along the backshore of the hapua, species diversity and composition would most likely be limited to those adapted to living in or on fine sediment (Clapcott *et al.,* 2011; Stora & Arnoux, 1983). This biota could include cyanobacteria mats. Other biota such as invertebrates could be eliminated as their feeding apparatus is clogged by the fine sediment.

If there were a change in algae biomass, there would be feedbacks on the stability of the substrate and water chemistry. With a more stable substrate, the fine sediment on the bottom of the hapua would be less easily suspended by wind driven circulation and the flow of the river. As a result, the concentration of phosphorus would be less influenced by the wind. Visual observations over the period of this study showed that vegetation can establish on the barrier in areas that have been stable for a couple of months. In the past, around the 1960s, the Rakaia River hapua had vegetation on some areas of the barrier (Hicks, 2012).

With the predicted increase in barrier stability post dam, more vegetation is likely to establish on the barrier. This would then further stabilise the barrier.

Dam developments on rivers can alter the area of available habitat for biota in coastal lagoons (Sklar & Browder, 1998). In Washington State, the loss of intertidal habitat has been linked to the change in river mouth morphology resulting from dam development on the Skokomish River (Jay & Simenstad, 1996). The amount of habitat available for biota in the Hurunui River hapua, especially periphyton, could increase post dam. As discussed, the variation in the surface area at different stages of the tide is less when the outlet is at the northern end of the hapua. With more substrate covered in water, a greater area would be available to inhabit. However, this would depend on how much the flows at the river mouth are reduced.

Overall, it is possible that the conditions post dam could favour periphyton as conditions become more favourable (Figure 8.9). An increase in temperature, substrate stability, nutrient concentrations, and light favours periphyton biomass accrual (Biggs, 2000). The potential for an increase in periphyton biomass could also increase due to a more stable substrate with the outlet at the northern end of the hapua, the outlet migrating less easily and frequently. Nutrients are likely to increase post dam with the increased availability of water and associated agriculture intensification. This would almost certainly increase surface and groundwater nutrient runoff into the Hurunui River and its tributaries. Any such increase in nutrients would favour periphyton growth. If periphyton biomass does increase, it is likely that there would be feedback effects on the chemistry of the water and animals (Sklar & Browder, 1998).

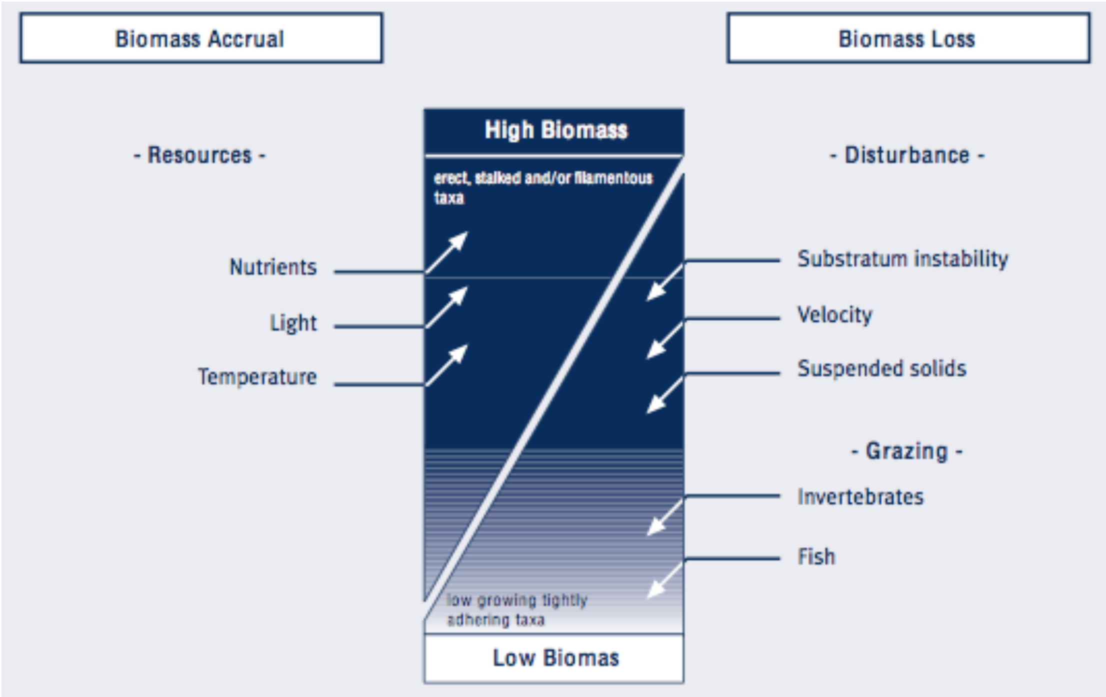

Figure 8.9: The effects of a change in resources and disturbances on the biomass of periphyton (Biggs, 2000, p. 32).

Ecological characteristics are difficult to compare between lagoons due to the variation in the: size, shape, fresh and saline water input, tidal influence, nutrient loading, seasonality, flushing rate, sediment processes, and temperature (Nixon, 1981). Because of this, it cannot be assumed that the effects of any changes in the ecology in one lagoon will be the same in another lagoon. This demonstrates the importance in developing site specific management protocols in terms of the ecology and waterway health due to the site specific physical, chemical, sediment, and geomorphological characteristics of each lagoon. It is recommended that more research be done to identify hapua species, and to understand the ecology of these systems.

8.5 Potential impacts in the coastal and marine environment

There is the potential for impacts to extend into the coastal and marine environment post dam development. Suspended sediment and nutrient levels were the greatest during the floods. Since a reduction in flood frequency and magnitude is expected post dam development, especially under the Hurunui proposal, there could be implications for coastal productivity (Young *et al.,* 2004). Productivity in the coastal environment has reduced at the mouths of many dammed rivers worldwide (Hu *et al.,* 1998; Humborg *et al.,* 2000; Sklar & Browder, 1998; Snoussi *et al.,* 2007). The effect on productivity in the coastal environment in this case is deemed to be minimal since the Hurunui River is a relatively small on a global scale, and it is possible that nutrients would continue to increase in the waterway as a result of agriculture intensification.

Sea level rise would also increase the pressure on this system. The incidence of barrier breaching is expected to increase in the presence of continued sea level rise and coastal erosion (Nicholas, 2003). As shown in the time-lapse images, the barrier decreases in elevation as waves wash over the barrier. The effect of this on the water quality in the hapua is likely to be minimal. This is because with the outlet at the northern end of the hapua, the flow throughout the hapua would allow for the seawater to have a small residence time. If the change in flow regime allows for ponded areas to become more prevalent, the effect of sea level rise and increased wave over washing on the quality of water in the hapua would be greater.

8.6 Management suggestions

While Kirk and Lauder (2000) and Kirk (1999) have to a limited extent addressed the management of coastal lagoons and lakes in New Zealand, so far, New Zealand has largely failed to address appropriate management for these systems. Coastal lagoons are the ecotone between marine, freshwater, and terrestrial ecosystems, and are regarded under the European Union Habitats Directive and the European Water Framework Directive as transitional waters. Although the development of water quality standards for managing coastal lagoons has been problematic internationally, attempts have been made to develop appropriate management protocols for these systems (Lucena-Moya *et al.,* 2012). There have been inconsistencies in the classification of water quality in coastal lagoons. While one lagoon has been classified as pristine by one standard, it has been classified as poor by another (Newton *et al.,* 2003). This highlights the importance of developing a management approach specific for each type of coastal lagoon.

In order to protect hapua, and preserve their health in the presence of pressures from both their catchments and the coastal environment, hapua must be managed as a unique system. Because hapua are directly impacted by activities both in the river catchment and at the coast, they cannot be regarded as either strictly fluvial or coastal. Because of this, hapua should be managed within an integrated management approach, taking into account a multitude of factors. Post dam impacts must take into account changes in the catchment involving the hydrological regime and land use. Natural factors such as climate change, sea level rise, and the interdecadal oscillation would also need to be taken into account. Both natural and anthropogenic factors need to be considered in order for the impacts of the dam on the hapua to be determined.

When determining the most appropriate management for hapua, values that are regarded as the most important must be decided. These values could include recreation, amenity, or ecology. For instance, if ecological values are regarded as the most important, management could focus on a few economically valuable species, or alternatively be focused on biodiversity (Sklar & Browder, 1998). Regardless of the values that are considered as the most important, hapua are complex systems that require a holistic and integrated management approach.

Because hapua are a unique ecosystem, they should be managed under their own specific water quality standards. Although the chemical nature of the water in hapua is similar to that of freshwater for most of the time, hapua are not strictly freshwater or marine. These standards could be similar to the guidelines and protocols that are currently used for rivers in New Zealand (ANZECC & ARMCANZ, 2000) and Canterbury (Environment Canterbury, 2011a), but should be altered to take into account marine influences. Coastal processes are the major control on the geomorphology of the hapua. The geomorphology then controls the water quality in different areas. Water quality standards must take into account the spatial and temporal variation in water quality that occurs 'naturally'. For instance, conductivity guidelines must allow for higher concentrations since elevated levels commonly occur as waves wash over the barrier. Guidelines must also take into account the influence of geomorphology on water quality. As this study showed, ponded areas have different water characteristics compared to unponded areas. Because of the distinct differences between ponded and unponded areas, monitoring of water quality in hapua should differentiate between the two areas. For instance, conductivity values are often much higher in unponded areas, therefore if spatial variation is not taken into account, the conductivity in the entire hapua could be over or under represented depending on where the sample sites are. Before any management guidelines are established, temporal variations in the physico-chemical characteristics in the water, especially seasonal variations must be understood in order to avoid the misapplication of management decisions (Lucena-Moya *et al.,* 2012).

8.6.1 Parameters for monitoring

Biota in coastal lagoons can be impacted by: river discharge, dissolved oxygen, pollutants, and sediment (Stora & Arnoux, 1983). Therefore, it is essential that a range of parameters be monitored if the effects on biota in the Hurunui River hapua post dam are to be determined. When ponded areas were present, some parameters indicated that the water was of poorer quality compared to areas that were close to the main current of the river. For instance, temperature and conductivity was higher in the ponded areas when the outlet was at the southern end of the hapua, indicating poorer water quality. Alternatively, the level of nutrients such as total nitrogen, nitrate + nitrite nitrogen and total phosphorus were lower in concentration in this area during flood conditions, indicating that the water quality was better in the ponded area. This demonstrates that while some areas may appear to be healthy compared to other areas based on one parameter, another parameter may indicate poorer water quality. Therefore a suite of parameters must be monitored to give an accurate idea of the effects of the dam on the hapua.

Water chemistry alone should not be used as a sole indicator of coastal lagoon health. In a study of coastal lagoons in NSW, Australia, it was shown that ranges of environmental indicators were needed to effectively study the water quality (Scanes *et al.,* 2007). Monitoring of nutrients must be carefully interpreted to exclude any interactions with other variables such as catchment geology. Monitoring programs must also take into account other factors such as land use in the catchment (Scanes *et al.,* 2007). Integrating biological assessments into a monitoring program would be of value. An extensive ecological survey of this lagoon must be done first to determine what species are present in the Hurunui River hapua.

In terms of nutrients, both nitrogen and phosphorus must be monitored, as they are good indicators of eutrophication (Lucena *et al.,* 2002). Field conditions, especially wind strength and water turbidity, must be taken each time that nutrient samples are taken since this study showed that phosphorus concentrations can be affected by wind driven circulation of the water. To avoid temporal variability, median nutrient concentrations should be recorded to reduce the influence of sudden peaks from high flow events (Lucena-Moya *et al.,* 2012). Sampling should also be done in low energy conditions since this is the most common state that the hapua experiences compared to floods and storms.

For the Hurunui River hapua, additional factors would need to be taken into account. This would include the irrigation season, which influences river flows and nutrient concentrations. Unlike many coastal lagoons and estuaries that have a relatively static morphology, hapua are different as their morphology is dynamic and can change significantly over a short period of time. This must be taken into account, especially when choosing sample sites. Depending on the fluvial and marine influences at the time, a site can have a minimal flow and soft substrate on one occasion, or have a swift flow with an armoured substrate on another occasion. This would make comparisons between the sampling events difficult as demonstrated in the present study.

8.6.2 Monitoring at different stages of the tide

The effect of tides on the concentration of suspended sediment and nutrients, as well as the values for temperature, conductivity, dissolved oxygen and pH was variable. Temperature and dissolved oxygen were not affected by the backwater effect of the tide. Alternatively, dissolved oxygen may be influenced by the tide in low energy conditions, although it is possible that the difference from high to low tide was due to other interacting factors and diurnal variation. None of the parameters were affected by the backwater effect of the tide during the floods.

The effect of the tide on the concentration of nutrients was also minimal. The difference in concentration between high and low tide was minimal compared to the overall mean concentration at each site. The greatest difference was for total phosphorus and dissolved reactive phosphorus, and this was attributed to the wind driven circulation and resuspension of fine sediment around mid tide in the second low energy event. Because the difference from high to low tide was minimal for the majority of the nutrients, and the chemical and physical water parameters, it is concluded that there is a minimal influence of the backwater effect of the tide on the concentration of nutrients. It is suggested that the time tide does not need to be taken into consideration when collecting samples and taking measurements.

8.6.3 Use of methods

A variety of methods were used in this study to investigate the influence of the tidal backwater effect and suspended sediment. Some of the methods were not useful. For suspended sediment, it is suggested that sediment traps are less useful due to the numerous limitations. Instead, water samples are the most reliable method. To monitor water temperature and its change from high to low tide, *in-situ* methods are the most reliable for this site. Although there is the potential for the thermal camera to be useful in investigating the backwater effect, its applicability and usefulness at this site is limited. This method would need to be further developed and refined in order for it to be used as a reliable method at this site.

8.6.4 Sample site selection

In terms of a monitoring program, it is suggested that site 1 be included as it gives an overall indication of the water quality in the lower river before the hapua. Instead of the site being on the true left of the river where access is difficult, it is suggested that this site be moved to the other side of the bridge. On the true right of the river is a concrete block that can be reached in low energy conditions, or a bank close by that can be sampled from in floods. Over the course of the study, the main channel was also on the true right of the river.

Site 2 could be included as a monitoring site depending on the objectives of the monitoring program. This site would be important to include if recreation is regarded as an important value as it is close to the campground.

If the quality of water entering the ocean is of interest, then the outlet should be monitored, otherwise this site could be excluded. If this site were to be monitored, measures would have to be put in place to ensure safety. This could include having two people at the site, wearing lifejackets, or only sampling this site in conditions deemed safe.

The backshore ponded site should be included as ponded areas have a susceptibility to have different water characteristics compared to sites that are unponded and closer to the main current of the river. This should be sampled along the backshore of the hapua, preferably where the substrate is not composed of fine sediment to avoid the influence of wind driven circulation of the water on phosphorus and suspended sediment concentrations. This site would need to be moved depending on where the ponded area is located.

Site 3 is an ideal site as it is usually about halfway along the length of the hapua, and fluctuates little in water level and the position of the shoreline. Depending on the aims of an investigation, this site could be either excluded or included. If the water quality in ponded vs. unponded areas is to be studied, site 3 should be used as this is in the main part of the hapua, unlike sites 1 and 2.

The time of tide would need to be taken into account when selecting sites since the backwater effect causes significant areas to be uncovered and covered in water at different stages of the tide. This would be the most evident when the outlet is at the southern end of the hapua. Sites would need to be chosen which are not significantly affected by the backwater effect of the tide.

8.7 Summary

The purpose of this chapter was to provide an integrated discussion of the results presented in the previous five chapters and to predict the changes that could occur in the hapua post dam development. These findings and potential changes were then used as the basis for management considerations and suggestions for future monitoring of this ecosystem.

The change in hydrological regime of the river post dam would alter the geomorphology of the hapua. Primary breach of the barrier at the southern end by floods would probably no longer occur under the Hurunui proposal, resulting in the outlet being maintained at the northern end of the hapua. The outlet would most likely be maintained at the northern end under the Waitohi proposal also due to the reduction in baseflow. As a result, the occurrence of outlet migration would reduce, as well as the area over which migration occurs. These changes would reduce the area of ponded areas. Uncertainties remain on how the persistence of the hapua over longer periods could change post dam.

The geomorphology of the hapua has direct implications for water quality involving water parameters such as temperature, conductivity, dissolved oxygen and pH, as well as nutrients, and sediment throughout the hapua. Water quality during low energy conditions is considered to be the best when the outlet is located at the northern end of the hapua and no ponded areas are present. Water quality, especially suspended sediment, total phosphorus, and dissolved reactive phosphorus can be affected by wind driven circulation and suspension of fine sediment from the bottom of the hapua.

The effect of the dams on sediment processes could be variable. Any change that does occur in the concentration of suspended sediment, sediment deposition and sediment composition would impact biota.

Hapua must be managed as a unique system with an appropriate management approach with specific water quality guidelines. It is inevitable that the Hurunui hapua will continue to evolve and change in response to external influences. Its location at the end of the river catchment makes it especially vulnerable. Despite the difficulties with separating natural and other anthropogenic effects from dam effects, attempts must be made to understand these systems more.

Biota such as periphyton in this hapua is dependent on a range of variables. Any change that does occur in any of the variables would have an effect on biota such as fish, algae, or invertebrates. There are many feedback processes that could also occur. Ecological processes within this ecosystem are complex. The biota post dam would be impacted by the change in geomorphology, spatial trends in water quality, and sediment processes.

Chapter 9: Conclusions

Hapua systems are complex and dynamic. While the geomorphology of these systems is well understood, little is known about the ecology and water characteristics of these vulnerable systems. The purpose of this research was to contribute to the existing information and research by investigating the current range of contemporary catchment and coastal processes, and the longer-term behaviour of the Hurunui River hapua using a multidisciplinary methodological framework. This was so that predictions could be made on how the proposed dams, and any changes in the river catchment could impact the Hurunui River hapua.

The primary objectives of this research were:

1. to examine and quantify the suspended sediment, water quality, and nutrient characteristics existing in different areas of the Hurunui hapua, under different energy conditions, and at different stages of the tide;

2. to examine substrate composition in different areas of the Hurunui hapua;

3. to determine where the majority of the sediment is currently transported, deposited and transferred to within the Hurunui hapua system;

4. to understand the geomorphic dynamics of the Hurunui hapua, including short-term (daily, event) and longer-term (decadal) cycles in Hurunui hapua behaviour, areal extent, shoreline position, and barrier width; and

5. to use investigation of monthly to annual trends in hydrology, nutrient concentrations, and other water quality parameters in the lower Hurunui River, and in significant wave height and direction along the Canterbury Coast in order to understand how the hapua system responds to these process agents.

The following chapter outlines the main findings and conclusions of this study, limitations, and future research suggestions.

9.1 Summary of main findings

9.1.1 Current hapua health

The current health of the Hurunui River hapua was investigated using a range of field techniques with regard to: sediment processes, water temperature, conductivity, dissolved oxygen, pH, and a range of nutrients. This took into account spatial trends, different energy conditions, and the backwater effect of the tide.

The greatest influence on the physical and chemical characteristics of the water, and sediment processes within the Hurunui River hapua is the flow of the river, and the shape of the hapua. The shape of the hapua is a product of fluvial and coastal processes.

The concentration of suspended sediment and nutrients is the highest during flood events, and generally lowest during low energy conditions. Suspended sediment and phosphorus can become elevated in concentration during low energy conditions if there is a strong wind that causes fine sediment on the bottom of the hapua to becomes suspended. Storms tend to decrease the concentration of nutrients due to the dilution effect of waves washing over the barrier.

The shape of the hapua controls the spatial variation in suspended sediment, nutrients, and water quality parameters in the Hurunui River hapua. The greatest amount of spatial variation occurs during floods when there are significant ponded areas present. Spatial differences in water temperature, dissolved oxygen, and conductivity only occur when the outlet is at the southern end of the hapua and ponded areas are present.

The deposition of fine sediment in this hapua depends on the magnitude of floods. This hapua acts as a fine sediment sink during small floods, but acts as a source of fine sediment during floods with a mean daily flow of around 535.6 m^3/s since fine sediment previously deposited by smaller floods is scoured from the landward shoreline of the lagoon.

At the time of sampling, most of the parameters were within guideline values during low energy conditions. However, this depends on the shape of the hapua and the energy condition. Parameters, especially nutrients, can exceed the guidelines during floods, and in areas that are close to the main current of the river. During floods, the concentration of nutrients is usually within the guidelines in areas that are ponded.

Overall, water quality tends to be 'good' during low energy and storm conditions. Water quality tends to be 'poor' during floods. Despite water quality in the Hurunui River hapua being within guidelines, this study did not take into account seasonal variations. The current health of this hapua must also be evaluated in relation to the trends in the river catchment, since there is a downstream decrease in water quality.

9.1.2 Current and historical hapua morphology and behaviour

Analysis of time-lapse images revealed additional information about the behaviour of the Hurunui River hapua. Breaching of the barrier appears to occur only in response to significant flood events. Despite the lagoon level rising to the top of the barrier during sea storms, breaching of the barrier did not occur. Fluctuation in the area of the hapua at different stages of the tide is the greatest when the outlet is located at the southern area of the hapua.

Aerial images showed that the surface area of the lagoon of the Hurunui River hapua fluctuates in size, and that changes in the surface area can be greater over shorter time periods such as two years, compared to longer time periods such as 30 years. The images showed that the size of the hapua, and the location of the outlet can be highly variable, and this reflects the dynamic nature of this system. The position of the shoreline, the position of the lagoonward shoreline of the barrier, and the width of the barrier has also been variable historically. All of these factors are likely to be related to the relative influence of fluvial and coastal processes at the time of image capture, therefore overall temporal changes are difficult to decipher.

9.1.3 Future of this system in the presence of dam development

Regardless of whether dams are to be developed in the Hurunui catchment or not, the health of the Hurunui River hapua must be considered, especially since there is a downstream decrease in water quality in this river. Water quality is likely to be compromised if there is an increase in agriculture and surface and groundwater runoff from these areas. Water quality in the hapua is also likely to be compromised if there is a change in the flow regime of the river. This study showed that the physical and chemical characteristics of the water, as well as sediment processes, are dependent on the flow of the river, and the morphology of the hapua. It is possible that the health of the hapua could be improved post dam if the outlet is maintained at the northern end of the hapua. However, the indirect effects and impacts of the dams must be taken into account when determining the impacts in the hapua.

While the hapua can be a valuable indicator of changes in the catchment and overall health of the system, its use as an indicator must be approached with caution due to the temporal and spatial variation that can occur in response to short term and rapid changes in the influence of external factors, and morphology of the system.

This study identifies the complex interaction between external influences and internal processes occurring at the Hurunui River hapua. In particular, the river regime, and the morphology of the river mouth, has vital implications on the temporal and spatial trends in water characteristics, sediment processes, and biota within the hapua. Therefore, it is essential that geomorphology, water quality, and the ecology of the system all be studied when determining the impacts of water development in hapua river catchments. Geomorphology and physical processes are essential to understand as they have a direct impact on the water quality in hapua and on the ecology. This demonstrates the importance of employing a holistic view when studying the ecotone between fluvial and coastal environments.

9.2 Limitations and future research

This study has sought to increase the understanding of the relationship between the river flow regime, and the geomorphology and ecosystem health and ecology at the river mouth. Gaps in the knowledge remain on the ecology of this hapua. This includes the species present, where they inhabit, and how they respond to change. Additional studies could identify species in the hapua that are particularly vulnerable to changes in the geomorphology of the hapua, and the associated changes in water quality and sediment processes. These species could be those with narrow and specialized ecological niches, rare and threatened species, and those with important roles in the ecosystem. This information is needed to adequately evaluate the impact of changes in the river catchment, and for effective management measures to be established. While the impacts on biota post dam have been predicted, these cannot be determined post dam without any detailed study of the biota before the dams are constructed, or significant changes in the catchment occur.

The water quality states in this study are based on only a limited number of events and morphological states of the hapua. It is possible, and likely, that there would be deviations from the water quality states discussed in this study due to the changes in the hapua morphology, and seasonal differences relating to river flow, irrigation season, and water residence time.

Finally, the range of interacting influences on the hapua must be understood so that the effects of dams on the hapua can be accurately determined. These include natural and climatic factors such as climate change, the interdecadal oscillation, and sea level rise. These factors also include anthropogenic factors such as changes in land use, and developments. Currently, there is a lack of research on how many of these impact hapua, in particular waterway health, over both short-term, and long-term scales.

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Appendices

Appendix 1. Details of the effects that the proposed dams could have on the Waitohi and Hurunui Rivers.

Under the Hurunui River proposal, water would be stored during the winter months, and the storage season may last up to 8 months of the year resulting in a reduction in flow variability (Hurunui District Council & Canterbury Water, 2010; Lin, 2009; Ward & Veendrick, 2009). Water would be released from the dams during the summer irrigation season, resulting in an increase in the frequency of higher flows and greater base flows during these months compared to current conditions (Lin, 2009; Ward & Veendrick, 2009). As a result, water availability would increase during the summer when flow is naturally at its lowest. Visual differences in the river flow would depend on the location along the river and the stage of irrigation season. Lin (2009) states that the change in flow regime would not be significantly different to the current conditions. It is also predicted that there would be a lower base flow at the river mouth as a result of an increase in water abstraction for irrigation (Lin, 2009).

It is inevitable that there would be an alteration in the flow regime and sediment processes if dams are constructed in the catchment of the Hurunui River. The potential changes in sediment processes are complex and depend on a variety of factors such as flow (water velocity and turbulence) and sediment properties (size and shape), and the location along the river (Chin, 2009). It is possible that there would be both positive and negative effects on periphyton and ecosystem health as a result of a change in sediment processes. Currently, periphyton can be a problem at the end of summer when river flow is typically at its lowest (Mosley, 2002). Flushing of this periphyton is reliant on both river flow and sediment loadings (Boffa Miskell Limited, 2009). After dam construction, the operating regime of the dam may allow for periphyton to be flushed in summer when it can be a problem, improving ecosystem health and amenity values during this period (Boffa Miskell Limited, 2009). However, this positive impact is unlikely to be observed at the river mouth due to water abstraction in the catchment resulting in lower flows at the river mouth as Mosley (2004) has identified that approximately 3 times the median flow is required to scour periphyton from the riverbed. Although there may be some positive changes on river health due to an alteration in sediment processes and transport post dam construction, the majority of the changes are likely to be negative. The reduction in sediment transport along with the reduction in flood frequency and magnitude could reduce the scouring of periphyton, and possibly leading to periphyton growth reaching nuisance levels (Hicks, 2011).

The proposed dams on the Waitohi River are likely to reduce baseflow, flood frequency, and flood magnitude only slightly. Under this scenario, the number of floods greater than the mean annual flood is expected to decrease by 10% (Christensen & Torgerson, 2012; Veendrick *et al.,* 2012). Flood magnitude would remain relatively unaffected due to a sediment-flushing regime which would allow floods 300 m^3/s to still occur and move down the Waitohi River during the winter (Christensen & Torgerson, 2012).

There are mixed opinions with regard to how the amount of sediment reaching the river mouth would change. The most accepted opinions are those that predict that the river mouth would be impacted as a result of a change in sediment transport and processes. Lin (2009) predicts that the decrease in river flood frequency and magnitude, as well as the reduction in baseflow at the river mouth due to water abstraction for irrigation, would significantly reduce the amount of sediment reaching the river mouth. It is also predicted that erosion would occur at the northern side of the river mouth, with the extent of the expected erosion still uncertain (Lin, 2009). Hicks (2011) supports a similar prediction that the amount of sediment delivered to the mouth of the Hurunui River would be reduced if the proposed dams for the Hurunui River are constructed because of a reduction in the magnitude and frequency of high flow events. Sediment from the catchment is an important source of sediment for the beaches north of the Hurunui River mouth. Breaking up of coarse bed load as it travels down the river also provides another source of suspended sediment (Hicks, 2011), so there is the potential for sediment supply to the coast to reduce if the majority of the coarse sediment is trapped behind a dam. Although coastal processes are the main acting force on hapua, flood events are important in delivering slugs of sediment down the river to the coast where it is then pushed into the barrier by waves and littoral currents (Hart & Bryan, 2008). While the change in sediment transport and processes has been investigated, the potential impacts of any changes at the river mouth, especially with regard to hapua ecosystem health have not yet been explored.

Overall, there is a lack of agreement with regard to the importance of the South Branch in terms of sediment supply and also the possible effects at the coast. Hicks (2011) states that the greatest source of sediment in the Hurunui Catchment is from the South Branch of the Hurunui River which is especially important in transporting large amounts of sediment during flood events to the mainstem of the Hurunui River (Canterbury Water *et al.,* 2011). Therefore if the proposed dams under the Hurunui River scenario are approved, there could be significant implications in terms of sediment supply and transport from the South Branch. As the South Branch transports the most sediment, the other options for water storage on a number of tributaries of the Hurunui River would have less of an effect on sediment transport to the coast (Hicks, 2011).

As with the Hurunui River, it is expected that there would be changes in sediment transport in the Waitohi River if the proposed scheme on for this river is approved (Christensen & Torgerson, 2012). There are also differing opinions on how the proposed dams on the Waitohi River could alter sediment transport. While the impacts are viewed as minor due to a sediment-flushing regime at two of the intakes, the alternative opinion is that there would be combined downstream impacts both in the Waitohi and Hurunui Rivers as well as at the coast. These impacts would be due to the reduction in transport capacity of the river (Christensen & Torgersen, 2011). It is predicted that the proposed dam options for the Waitohi River would have less of an impact on sediment processes than the proposed dams on the South Branch of the Hurunui River and the dam at Lake Sumner (Environment Canterbury, 2011f). Although it is predicted that the majority of the sediment prevented from being transported downstream would be fine sediment, coarse sediment would also be prevented from moving downstream. However, the flushing regime in the proposed developments for the Waitohi River should ensure the continued movement of the majority of coarse sediment to the coast where it is important for nourishing the adjacent beaches (Christensen & Torgersen, 2011). Despite the suggested mitigation measures to ensure continued transport of sediment downstream, the significance of a change in sediment transport on the river mouth and the coastline has not adequately been taken into account.

While a river fluctuates through erosional, depositional and stable states over space (for example an entire drainage system or only a section of a river) and time (for example short term cycles, modern or geologic) (Schumm & Lichty, 1965), the deviation from natural cycles should not be ignored. Although it is likely that there would be differences in sediment transport and deposition/erosion in different areas of the river, the overall impact on sediment supply to the hapua and coastal environment must be determined in order to predict the impacts on the hapua ecology, morphology and dynamics.

The Hurunui River is a significant habitat for many native as well as introduced species (Mosley, 2002). It has been well highlighted that there is the potential for significant effects on the ecology of the Hurunui River as well as Lake Sumner if the proposed dams are to be constructed. However, all of the studies so far have focused on the impacts within the river catchment and none have specifically focused on the potential effects on the biota at the river mouth. Some of the ecological surveys were also carried out only throughout the summer months and have a number of associated assumptions with regard to flow regimes. While it is important to determine how the areas closest to the developed sites would be affected, it is important not to disregard impacts further down the river and at the coast since the fluvial and coastal systems are interconnected. The studies have investigated the potential effects on both terrestrial and aquatic flora and fauna, and the majority of the potential effects have been highlighted as being negative.

The majority of the potential impacts from the Hurunui River proposal would involve the inundation of habitats along the edges of Lake Sumner, but also involve the loss of habitat from the construction of the dams (Boffa Miskell Limited, 2009). Both the South Branch dam and the Lake Sumner dam will result in the inundation of flora and fauna habitats. The Hurunui River catchment has both native plants such as *Pittosporum patulum* and pest plants such as gorse (Boffa Miskell Limited, 2009). The catchment also contains a high number of threatened native bird species such as the black-fronted tern/tarapirohe, fish species such as the longfin eel, and invertebrates (Armstrong, 2006). Many introduced species such as possums, deer, rainbow trout, and Canadian geese are also present along this river (Armstrong, 2006; Mosley, 2002). The inundation of approximately 7 km of braided river would affect a number of bird species that are dependent on braided river habitats (Boffa Miskell Limited, 2009). Some bird species such as Banded Dottrell are also at risk from the dam developments as they are reliant on freshes to clear vegetation from the braided islands to ensure safe sites for nesting (Mosley, 2002).

There are also predicted impacts on biota if the Waitohi River is to be dammed (Boffa Miskell Limited, 2012). Although there is a limited amount of information on the impacts on birds, it is likely that some habitat important for feeding, breeding and roosting will be inundated. It is expected that there would be some inundation of lizard and terrestrial invertebrate habitat, but overall the impacts are thought to be minimal. The greatest impact of the proposed dams on this river is expected to be on aquatic species, especially in terms of fish passage (Boffa Miskell Limited, 2012).

It is evident that there is a lack of knowledge about the potential effects that the proposed dams in the Hurunui-Waiau region could have on the Hurunui hapua and the coastal environment. Assessments of environmental effects have focused almost solely on the river catchment and only a limited few have taken into consideration the potential impacts at the coast (Chin, 2009; Christensen & Torgersen, 2011; Hicks, 2011; Lin, 2009). Coastal lagoons are sensitive to changes in their catchments (Hart & Bryan, 2008), so although it is evident that the proposed dams could have a significant impact within the river catchments, the impacts at the river mouths must not be ignored. These lagoons could potentially act as an indicator of the health of the overall catchment. With an increase in coastal development, as well as within river catchments, the pressure on coastal lagoons is only likely to increase (Hart & Bryan, 2008). Development along the east coast of the south island is increasing, and this is evident close to the Hurunui River mouth hapua. A small community of houses as well as a campground is present at the Hurunui River mouth, and approximately 10km north is Gore Bay, an increasingly popular holiday destination. Because river mouths can be impacted by both coastal and river activities, fluvial and coastal systems cannot be regarded as separate systems, instead they must be viewed as interconnected (Hart & Bryan, 2008).

To adequately identify the effects of dams or irrigation in the catchments of rivers on hapua, baseline information about the ecology, processes and natural cycles must be gathered and understood so that comparisons can be made and any changes detected.

Appendix 2: The number of months per year which nutrient data exists (Environment Canterbury records) for the SH1 site on the Hurunui River.

Year	Total nitrogen	Ammonia nitrogen	Nitrate + nitrite nitrogen	Total phosphorus	Dissolved reactive phosphorus
2001	7	7	7	6	7
2002	2	2	2	4	2
2003	0	0	0	0	0
2004	0	0	0	0	0
2005	9	4	9	5	9
2006	11	9	11	7	11
2007	12	12	12	6	12
2008	12	9	12	5	11
2009	12	11	12	5	12
2010	12	10	12	6	10
2011	11	6	9	8	7
2012	10	9	10	5	10

Appendix 3: Summary of water quality data collected at the SH1 site on the Hurunui River in three different time periods (data from Hayward, 2001).

	January 1989-December 1999		August 1993-June 1999		January 2001-August 2012*	
	mean	**median**	**mean**	**median**	**mean**	**median**
Dissolved oxygen	11.0	11.0	11.1	11.1	11.5	11.4
pH	7.9	7.9	7.8	7.8	8.0	7.9
Temperature	12.0	11.5	11.1	10.8	12.0	12.1
Nitrate + nitrite nitrogen	0.265	0.24	0.281	0.28	0.376	0.331
Ammonia nitrogen	0.005	0.005	0.011	0.011	0.02	0.01
Total nitrogen	0.356	0.317	0.439	0.369	0.447	0.403
Dissolved reactive phosphorus	0.003	0.002	0.006	0.004	0.006	0.004
Total phosphorus	0.045	0.012	0.04	0.013	0.046	0.019

* not all months and years contain data for each parameter

Appendix 4. Details of sampling sites for suspended sediment and water parameters.

Low energy conditions – 1st event 13 May 2012 (left), and 2nd event 24 September 2012 (right)

Site	Northing	Easting
1	5249389.33	1622376.53
2	5249037.75	1622819.87
3	5249505.66	1623566.39
4	5250052.53	1623913.52
5	Was not recorded	Was not recorded

Site	Northing	Easting
1	5249389.33	1622376.53
2	5249037.75	1622819.87
3	5249505.66	1623566.39
4	5250052.53	1623913.52
5	5249045.07	1623240.09

Flood conditions 25 June 2012 (left), storm conditions 7 November 2012 (right)

Site	Northing	Easting
1	5249452.78	1622372.71
2	5249039.98	1622828.95
3	5249505.77	1623563.53
4	5250039.06	1623900.45
5	na	na

Site	Northing	Easting
1	5249446.08	1622366.21
2	5249035.43	1622821.07
3	5249508.40	1623565.49
4	5250044.93	1623904.13
5	5249039.02	1623219.27

Appendix 5. Details of the sediment trap locations and sampling dates.

Date	Sites				River flow (m3/s)
	1	2	3	4	
13 May 2012		√	√		35.8
24 May 2012	√	√	√		28.8
25 May 2012	√	√	√		28.2
13 July 2012	√	√	√	√	86.6

Appendix 6. Sample dates for the sediment composition samples.

Site	Date of sampling	
	Low energy conditions	After a flood
1	24 May 2012	
2	13 July 2012	27 June 2012
3	14 May 2012	27 June 2012
4	14 May 2012	27 June 2012
5	14 May 2012	

Appendix 7. Nutrients sample site locations.

Low energy conditions – 1st event 13 July 2012 (left) and 2nd event 24 September 2012 (right)

Site	Northing	Easting
1	5249452.78	1622372.71
2	5249035.76	1622835.08
3	5249506.82	1623565.15
4	5250057.02	1623910.78
5	5250308.05	1624297.71

Site	Northing	Easting
1	5249389.33	1622376.53
2	5249037.75	1622819.87
3	5249505.66	1623566.39
4	5250052.53	1623913.52
5	5249045.07	1623240.09

Flood conditions 2 August 2012 (left), and storm conditions 7 November 2012 (right)

Site	Northing	Easting
1	5249389.33	1622376.53
2	5249037.75	1622819.87
3	5249505.66	1623566.39
4	5250151.06	1624075.57
5	5250048.93	1623935.89

Site	Northing	Easting
1	5249389.33	1622376.53
2	5249035.43	1622821.07
3	5249508.40	1623565.49
4	5250044.93	1623904.13
5	5249039.02	1623219.27

Appendix 8. Site locations and length of deployment for the time lapse cameras and water level recorder.

Equipment	Northing	Easting	Recording period
Time lapse camera – South end of hapua	5248891.94	1622912.03	2 May 2012 – 30 January 2013
Time lapse camera at road end	5249499.41	1623550.76	22 June 2012 – 30 January 2013
Water level recorder	5249181.77	1623222.71	22 June 2012 – 7 November 2012

Appendix 9: Aerial photographs used

Date	Survey number	Run and frame	Scale	Source
25/12/1974	SN 5370	L/30	1:26,500	Environment Canterbury
02/07/1993	SN 114	Run A # 83	1:19,000	Environment Canterbury
03/09/1995	SN 12206	DD/32	1:27,000	Environment Canterbury
2002/2003*				LINZ
2004/2005*				LINZ

* Exact date of the image capture is unknown, but it likely to have occurred sometime around Christmas.

Appendix 10: Suspended sediment (mg/L) data (low energy event 1: 13 May 2012, low energy event 2: 24 September 2012, flood 1: 25 June 2012, flood 2: 9 August 2012, storm: 7 November 2012).

		Low energy 1	Low energy 2	Flood 1	Flood 2	Storm
High tide	1	0.0018	0.00355	0.21251	0.91415	0.02264
		0.0027	0.01535	0.18203	1.1077	0.22244
		0.00121	0.0121	0.20237	0.93318	0.02128
	2	0.00172	0.02447	0.85402	0.82887	0.01761
		0.00261	0.01784	0.26874	0.84892	0.01649
		0.00253	0.02294	0.25071	0.85214	0.01974
	3	0.00237	0.04356	0.14769	0.13413	0.02171
		0.00439	0.05175	1.13386	0.14108	0.02059
		0.00227	0.07856	0.4157	0.13344	0.02031
	B	0.00101	0.0087	0.16591	0.10074	0.02911
		0.00125	0.00713	0.23045	10262	0.029
		0.0018	0.00661	0.19906	0.10073	0.02815
	O	0.00177	0.00883			0.90438
		0.00187	0.00882			0.02497
		0.00182	0.0105			0.02705
Mid tide	1	0.00321	0.01955	0.19399	0.93806	
		0.00246	0.01584	0.17464	0.76745	
		0.00235	0.02266	0.17508	0.84774	
	2	0.00303	0.0298	0.25141	0.75274	
		0.00234	0.02203	0.73543	0.75068	
		0.00172	0.02457	0.36335	0.86922	
	3	0.0057	0.00703	0.20808	0.10049	
		0.00294	0.00559	0.45924	0.11509	
		0.00172	0.00584	0.28234	0.08618	
	B	0.00216	0.14535	0.14592	0.14162	
		0.00115	0.10855	0.18268	0.08255	
		0.00598	0.12263	0.16665	0.07814	
	O	0.00309	0.02033			
		0.00139	0.02096			
		0.00175	0.01649			
Low tide	1	0.00308	0.0156	0.18919	0.79674	
		0.00193	0.01431	0.17781	0.74611	
		0.01281	0.01812	0.16183	0.73676	
	2	0.0021	0.02302	0.36173	0.64262	
		0.0026	0.01508	0.22414	0.80462	
		0.00176	0.01744	0.21301	0.75885	

	3	0.00188	0.11705	0.86707	0.08182	
		0.00212	0.14287	0.18303	0.0849	
		0.00287	0.1702	0.29258	0.0913	
	B	0.00271	0.01333	0.15737	0.0758	
		0.00428	0.00679	0.15403	0.06001	
		0.0047	0.00705	0.14105	0.15649	
	O	0.00192	0.03651			
		0.00224	0.03625			
		0.00118	0.03502			

Appendix 11: Water temperature (°C) data taken at the same time as suspended sediment samples.

		Low energy 1	Low energy 2	Flood 1	Flood 2	Storm
	1	10.95	11.55	6.23	7.72	12.55
		10.98	11.55	6.25	7.73	12.51
		11	11.54	6.25	7.73	12.47
	2	10.83	11.92	6.16	7.73	11.48
		10.92	12.02	6.16	7.73	11.36
		10.84	12.19	6.16	7.73	11.24
	3	10.68	12.13	6.08	8.6	11.2
High tide		10.62	12.13	6.08	8.59	11.33
		10.73	12.11	6.1	8.6	11.42
	B	10.18	11.88	6.03	8.74	11.06
		10.17	11.76	6.01	8.74	11.12
		10.64	11.7	6.01	8.74	11.22
	O	9.64	11.35			12.32
		9.62	11.43			12.47
		9.68	11.51			12.66
	1	11.47	12.32	6.68	7.97	
		11.47	12.31	6.68	7.97	
		11.46	12.29	6.69	7.97	
	2	11.66	13.09	6.64	7.97	
		11.62	13.14	6.64	7.97	
		11.65	13.29	6.65	7.97	
Mid tide	3	11.14	11.8	6.45	9.46	
		11.1	11.67	6.48	9.4	
		11.17	11.62	6.49	9.31	
	B	10.25	11.66	6.25	9.06	
		10.18	11.66	6.26	9.1	
		10.16	11.59	6.28	9.12	
	O	10.64	12.69			

		10.54	12.69			
		10.6	12.72			
	1	11.25	12.18	6.89	7.99	
		11.24	12.18	6.89	7.98	
		11.23	12.18	6.89	7.98	
	2	11.45	12.25	6.89	8.05	
		11.4	12.2	6.89	8.05	
		11.39	12.2	6.89	8.04	
	3	11.54	11.14	6.83	9.51	
Low tide		11.43	11.1	6.83	9.54	
		11.46	11.06	6.83	9.55	
	B	10.48	11.31	6.67	9.51	
		10.5	11.27	6.68	9.51	
		10.41	11.25	6.72	9.54	
	O	10.99	12.18			
		11.1	12.16			
		11.18	12.12			

Appendix 12: Conductivity (uS/cm) data taken at the same time as the suspended sediment samples.

		Low energy 1	Low energy 2	Flood 1	Flood 2	Storm
	1	98.2	95	73.3	90.2	94.6
		98.2	94.4	73.3	90.7	94.5
		98.4	95.1	73.3	90.3	94.6
	2	98.4	94.9	72.8	92.3	93
		98.2	95.1	73.1	92.4	93.2
		98.3	94.6	73.3	92.6	92.7
	3	101.8	358.5	72.7	14650	4817
High tide		101.2	355.8	73	14190	4816
		100.5	356.2	72.6	14620	4822
	B	117.7	970	73.9	18230	9752
		117.8	970.3	72.6	18330	9747
		115.2	969.4	72.7	18490	9755
	O	98.9	96.5			12410
		98.9	96.4			12390
		100.2	96.4			12330
	1	97.9	94.5	73.7	90.6	
Mid tide		98.3	94.8	73.3	90.5	
		98.2	94.8	73.4	90.3	

	2	98.7	96	73.4	91.9	
		98.5	95.7	73.5	91.8	
		98.5	96.1	73.4	91.4	
	3	100.1	525.9	73.1	17650	
		100.7	526.2	73	17850	
		100.1	525.4	73.2	17620	
	B	108.9	740.8	73.9	17180	
		108.4	741.3	73.5	17040	
		107.8	742.1	73.5	17010	
	O	99.1	103.6			
		99.3	104.1			
		99.4	104.8			
Low tide	1	98.3	94.5	73.5	91	
		98.4	94.6	73.9	91.6	
		98.4	94.5	73.6	91.2	
	2	98.8	95.9	74.1	92	
		98.5	96.3	74.3	92.1	
		98.5	96.1	74.2	92.2	
	3	102.7	603.2	73.9	19010	
		104.5	603.6	73.7	19640	
		104.2	603.8	73.9	19730	
	B	101.8	858.3	74.1	17820	
		102.1	858.3	73.8	17970	
		102	857.6	74	17970	
	O	98.7	107			
		99	106.9			
		99.4	107			

Appendix 13: Dissolved oxygen (mg/L) data taken at the same time as the suspended sediment samples.

		Low energy 1	Low energy 2	Flood 1	Flood 2	Storm
High tide	1	14.6	9.03	20.53	15.17	10.05
		14.1	8.62	18.09	13.37	10.04
		11.61	8.35	16.98	12.92	10.05
	2	11.24	12.65	20.57	14.22	9.6
		16.85	12.3	19.24	13.27	9.69
		14.54	12.08	18.85	12.81	9.79
	3	17.99	11.29	25.01	13.38	8.97
		17.16	10.78	20.31	11.27	8.56
		15.54	10.59	18.46	14.73	8.41
	B	18.55	10.08	17.41	11.84	10.16

		11.37	9.67	16.81	11.45	8.91
		18.72	9.39	16.8	11.42	8.55
	O	12.44	10.03			9.37
		11.49	9.69			9.48
		18.91	9.65			9.5
	1	11.47	8.17	18.64	13.03	
		11.47	8.06	17.73	12.56	
		11.46	8.09	17.46	12.38	
	2	12.94	10.09	18.36	14.86	
		12.66	10.05	17.6	13.35	
		12.55	12.08	17.07	12.82	
	3	11	11.04	18.64	12.35	
Mid tide		10.89	10.37	17.46	11.42	
		10.19	10.2	16.85	13.7	
	B	10.34	10.16	19.62	12.05	
		10.59	9.84	16.31	10.76	
		10.64	9.69	14.98	10.5	
	O	30.83	12.63			
		11.18	11.04			
		10.89	10.59			
	1	15.1	10.51	16.08	13.66	
		15.07	10.49	15.68	13.05	
		14.46	10.51	15.69	12.91	
	2	11.46	9.77	16.6	14.76	
		11.39	9.16	16.13	13.1	
		11.36	9.11	15.84	12.87	
	3	18.33	9.43	17.03	12.16	
Low tide		10.57	9.1	16.44	10.86	
		10.93	9.18	16.03	10.47	
	B	10.81	9.02	17.54	12	
		9.15	9.06	17.67	11.01	
		9.38	9.11	17.31	10.87	
	O	12.45	10.64			
		10.96	10.24			
		10.69	10.01			

Appendix 14: pH data taken at the same time as the suspended sediment samples.

		Low energy 1	Low energy 2	Flood 1	Flood 2	Storm
	1	8.17	7.77	7.64	7.91	7.91
		8.2	7.76	7.68	7.71	7.86
		8.09	7.75	7.64	7.67	7.84
	2	8.05	7.83	7.68	7.87	7.79
		8.53	7.79	7.65	7.74	7.73
		7.84	7.77	7.64	7.7	7.71
	3	7.98	7.93	7.9	7.85	8.26
High tide		8.17	7.91	7.79	7.78	8.23
		8.01	7.91	7.71	8.15	8.21
	B	7.96	8.27	8.22	7.82	8.35
		7.64	8.24	7.86	7.83	8.35
		7.92	8.23	7.86	7.84	8.35
	O	8.08	7.83			8.26
		7.88	7.79			8.26
		7.69	7.79			8.25
	1	8.22	7.82	7.55	7.69	
		8.23	7.81	7.59	7.66	
		8.33	7.8	7.59	7.65	
	2	8.1	7.9	7.57	8.11	
		7.91	7.84	7.59	7.84	
		8.12	7.83	7.6	7.75	
	3	7.99	8.07	7.66	7.83	
Mid tide		7.73	8.07	7.86	7.79	
		7.72	8.07	7.68	8.05	
	B	7.74	7.94	7.62	7.83	
		7.74	7.95	7.66	7.8	
		7.7	7.96	7.66	7.8	
	O	8.84	7.95			
		8.1	7.91			
		8.09	7.91			
	1	8.11	7.81	7.59	7.74	
		8.11	7.8	7.6	7.67	
		8.09	7.8	7.61	7.66	
Low tide	2	8.09	7.87	7.58	7.92	
		8.2	7.81	7.6	7.7	
		8.19	7.81	7.6	7.68	
	3	8.7	8.17	7.77	7.98	

		8.26	8.17	7.68	7.87	
		7.96	8.17	7.67	7.86	
	B	8.11	8.14	7.68	7.85	
		8.09	8.15	7.81	7.82	
		8.05	8.16	7.96	7.82	
	O	8.16	7.99			
		8.19	7.99			
		8.21	8			

Appendix 15: Nutrient concentrations (mg/L) data in low energy event 1 (13 July 2012).

		TN	NH_3N	NNN	TP	DRP
High tide	1	0.39	0.025	0.4	<0.008	0.001
	2	0.43	0.014	0.33	<0.008	0.004
	3	0.32	0.016	0.3	<0.008	0.004
	B	0.45	0.02	0.29	<0.008	0.003
	O	0.44	0.02	0.28	<0.008	0.003
Mid tide	1	0.4	0.02	0.39	<0.008	0.002
	2	0.46	0.029	0.37	<0.008	0.002
	3	0.4	0.02	0.39	<0.008	0.002
	B	0.44	0.036	0.38	<0.008	0.009
	O	0.32	0.021	0.26	<0.008	0.003
Low tide	1	0.41	0.019	0.4	<0.008	0.002
	2	0.39	0.014	0.4	<0.008	0.001
	3	0.4	0.016	0.37	<0.008	<0.001
	B	0.41	0.017	0.39	0.008	<0.001
	O	0.42	0.018	0.39	<0.008	<0.001

Appendix 16: Nutrient concentrations (mg/L) data in low energy event 2 (24 September 2012).

		TN	NH_3N	NNN	TP	DRP
High tide	1	0.41	0.011	0.36	0.012	0.002
	2	0.4	0.018	0.39	0.009	0.002
	3	0.44	0.016	0.36	0.058	0.019
	B	0.36	0.008	0.33	0.004	0.001
	O	0.52	0.014	0.35	0.012	0.003
Mid tide	1	0.49	0.009	0.35	0.004	0.002
	2	0.4	0.009	0.37	0.004	0.001
	3	0.41	0.01	0.41	0.063	0.003
	B	0.44	0.012	0.37	0.012	0.002
	O	0.45	0.013	0.35	0.02	0.002
Low tide	1	0.38	0.011	0.39	0.004	0.002
	2	0.42	0.012	0.37	0.01	0.003
	3	0.54	0.008	0.47	0.08	0.003
	B	0.52	0.008	0.43	0.004	0.002
	O	0.42	0.015	0.35	0.023	0.002

Appendix 17: Nutrient concentrations (mg/L) data in the flood (2 August 2012) and storm (7 November 2012) events.

		TN	NH3N	NNN	TP	DRP
Flood	1	0.87	0.027	0.43	0.91	0.02
	2	0.9	0.025	0.38	0.92	0.035
	3	0.88	0.038	0.34	0.73	0.027
	B	0.35	0.042	0.18	0.12	0.021
	O	0.96	0.044	0.36	1	0.036
Storm	1	0.19	0.006	0.2	0.014	0.003
	2	0.17	0.008	0.2	0.018	0.007
	3	0.23	0.008	0.15	0.015	0.003
	B	0.21	0.009	0.1	0.02	0.004
	O	0.19	0.013	0.11	0.018	0.004